Flooding in Hinksey Park Ward, Oxford

David Macdonald, Independent Consultant



Project Groundwater
Are you flood resilient?

EXECUTIVE SUMMARY

Project Groundwater (PG) is a six-year Defra-funded programme working with communities in high-risk flood areas in Oxfordshire, Buckinghamshire, Luton, West Berkshire and Hertfordshire. It is led by Buckinghamshire Council in partnership with local authorities and Flood Community Groups. The programme aims to drive innovation in flood and coastal resilience and adaptation to a changing climate, specifically transforming how communities prepare and respond to groundwater flooding. Although much of the focus of the project is Chalk groundwater flooding, it is also assessing Permeable Superficial Deposit (PSD) groundwater flooding. PSD groundwater flooding occurs as a result of abnormally high groundwater levels in areas that are underlain by shallow unconsolidated aquifers. The high groundwater is primarily driven by levels in rivers in good hydraulic connection with the same shallow aquifers.

Management of flood risk in areas prone to PSD groundwater flooding is challenging. In the context of PSD groundwater flooding, PG has not set out to develop an operational warning system for communities, as has been possible for those in Chalk settings. The objective has been to explore the options that might be effective in PSD settings and provide advice to the Environment Agency and Lead Local Flood Authorities. This report uses a data-rich case study of Hinksey Park Ward (HPW) in South Oxford to help address this objective. Groundwater flooding cannot be addressed in isolation, especially in floodplain settings prone to PSD groundwater flooding. Flood events involve a complex spatiotemporal mix of both groundwater and fluvial flooding and therefore the investigation of HPW looks at flooding holistically.

HPW is located in the south of the City of Oxford, primarily to the south and west of the River Thames and to the east of Hinksey Stream. The Ward has an area of 2.35 km^2 and the population at the time of the 2021 Census was 5,578. There are approximately 2,600 properties in the Ward, the majority of which are domestic. The whole of the area sits on the alluvial deposits of the current River Thames floodplain. The study identified 13 flood events that have occurred since 1998 that have had substantial impacts on HPW and are referred to in the report as 'major'. In all cases these major flood events have included widespread groundwater flooding impacting habited zones of tens of properties and the sewerage and wastewater systems servicing hundreds of properties.

The analysis undertaken has shown the complexity of flooding that occurs in HPW, as a result of the number of rivers and streams that border it and their differing catchment responses to rainfall. Although it has been possible to identify individual threshold river levels at upstream river stations that coincide with periods of major floods in HPW, the lags between the levels at these river stations and at those local to HPW during high flow periods were both short, in the order of 12 hours at best, and inconsistent. The expected strong correlation between local river levels and groundwater levels beneath HPW is confirmed, with lag times between the two ranging between a few and 20 hours. Although the EA Flood Warning Service for the area has identified all major flood events since it has been running, based on the local flood thresholds estimated through this study, the lead-in times provided by the Service are highly variable and also have been very short on occasions.

The results of the study indicate that for a less hydrologically complex locations elsewhere, live upstream river levels accessible through the EA could be used for effective groundwater flood warning. It is unlikely, however, that early warning systems can be implemented without some local knowledge that brings detailed understanding of flood receptors and information on past events. Although not explored in detail in the report, it is suggested that for the more complex HPW case, extrapolation of rising hydrographs could be undertaken at upstream river stations during floods, to show whether a developing flood is likely to be significant and providing days rather than hours of warning should that be the case. This approach has been applied successfully by the South Oxford Flood Action Group, using live upstream river levels along with live local groundwater and stream levels obtained through infrastructure funded by PG.

ACKNOWLEDGEMENTS

This report has been prepared by David Macdonald, an Independent Consultant, for Buckinghamshire Council to help meet the aims of Project Groundwater.

The author would like to thank those residents of South Oxford who have contributed to this study with both their time and insights. Thanks are due to the Project Groundwater team, from Buckinghamshire Council, Jacobs and Groundwork for their direction and support. The Project Groundwater team is also thanked for their encouragement and funding that have enabled the establishment and development of the South Oxford Flood Action Group (SOFLAG). SOFLAG has both informed and benefitted from this study. The study would not have been possible without the years of funding provided by both the Natural Environment Research Council, through the British Geological Survey, and the Environment Agency, that allowed lengthy and widespread monitoring of aspects of the hydrology of the Oxford floodplain, and interpretation of the resulting data. Andy Dixon of Groundwater Monitoring and Development Ltd. is also acknowledged for driving efforts to improve the understanding of the hydrology within this area over many years.

TABLE OF CONTENTS

Executive Summary i
Acknowledgements ii
1 Introduction 1
2 Conceptual Model 2
2.1 Introduction to conceptual modelling 2
2.2 Information and data sources 2
2.2.1 National hydrometeorological monitoring network and spatial mapping 2
2.2.2 Local flood-related studies 9
2.2.3 Local flood impact data 9
2.3 Contextual information 10
2.3.1 Physical features, including surface water network 10
2.3.2 Geology and hydrogeology 12
2.3.3 Hydrological data 12
2.3.3.1 Groundwater-surface water interaction 12
2.3.3.2 Groundwater depths 16
2.3.3.3 Surface water levels and groundwater responses during flood periods 16
2.3.4 Flood impact and protection measures 20
2.3.4.1 Sewerage and stormwater system 21
2.3.4.2 Basement flooding 21
2.3.4.3 Direct inundation from fluvial flood waters 21
2.3.4.4 Gardens and outbuildings 22
2.4 Flood conceptualisation, mechanisms and sequencing 22
2.4.1 Flood conceptualisation 22
2.4.2 Further detail on mechanisms and sequencing 24
2.5 Knowledge gaps 32
3 Potential for Flood Early Warning in HPW 32
3.1 Introduction to flood early warning 32
3.2 Correlation between river and groundwater levels during floods 33
3.3 Flood characteristics 36
3.4 Towards early warning 49
3.4.1 Flood thresholds at HPW 49
3.4.2 EA Flood Warning for South Oxford area 50
3.4.3 Developing flood warnings 51
4 Way forward 53
4.1 Hinksey Park Ward 53
4.2 Wider application 54
5 References 56

LIST OF FIGURES

Figure 2-1 Hinksey Park Ward (red polygon), the boundary for the Project Groundwater community. Blue arrows show direction of river/stream flow. 3

Figure 2-2 a) River catchments and EA rainfall stations; b) EA river stations referred to in report; c) EA river stations within the Oxford floodplain, and groundwater and river monitoring sites used within analysis included in report 6

Figure 2-3 LiDaR elevation in mAOD for HPW (white polygon) 7

Figure 2-4 1:50K bedrock and superficial geology for HPW area 8

Figure 2-5 Thickness of made ground above the natural flood plain (from Macdonald et al., 2012). The areas of Grandpont, New Hinksey and Cold Harbour are indicated. HPW is enclosed within the dashed box 11

Figure 2-6 Thickness of Northmoor Sand & Gravels (left) and Alluvium (right) in the Oxford area (from Newell, 2008). HPW is enclosed within dashed box 13

Figure 2-7 a) Seacourt Stream water level and groundwater level in a borehole completed in the sand and gravel deposits a few metres from the stream; b) River Thames water level and adjacent groundwater levels at Yarnton Mead in the northern part of the Oxford floodplain. Boreholes are a few metres (bh1), ~300 m (bh2) and ~500 m (bh3) from the River Thames. (from Macdonald et al., 2018) 14

Figure 2-8 a) contoured groundwater levels and groundwater flow lines in the floodplain gravel aquifer; and b) depth to groundwater within the gravel aquifer. Both maps based on measurements in May 2007 (from Macdonald et al., 2018). HPW is enclosed within the dashed box. 15

Figure 2-9 Most complete groundwater level time series dataset available for HPW, from borehole NH1, as well as timings of major flood events for this period (black dots). Red line indicates the periods for which data are available. Note, from 2012 onwards the sensor was positioned at a depth that meant it did not capture groundwater levels with an elevation below approx. 54.4 mAOD 17

Figure 2-10 River and groundwater hydrographs for the July 2007 flood event. Note, Hinksey Stream, Thames, Weirs Mill Stream and gwl are: DSH3, Iffley Lock (upstream), DIFA and NH1 monitoring sites, respectively. See Figure 2.2 for monitoring site locations 18

Figure 2-11 River and groundwater hydrographs for the November 2012 flood event. Hinksey Stream, Thames, Weirs Mill Stream and gwl are: DSH3, Iffley Lock (upstream), DIFA and NH1 monitoring sites, respectively. See Figure 2.2 for monitoring site locations. Note, data from Iffley Lock (upstream) are missing during the period of 27-29 November. 19

Figure 2-12 Groundwater hydrographs for borehole NH1 and ground flood water level (FNH1) in the vicinity during the July 2007 flood event 19

Figure 2-13 Flooded areas and flood water flow routes at the peak of a typical event in HPW (dashed orange line is the position of the vertical section shown in Figure 2.14) 20

Figure 2-14 West-east cross-section schematic through HPW showing typical ground and building elevations, as well as geology and river and groundwater level. Line of section is shown in Figure 2.13 24

Figure 2-15 Areas referred to in description of mechanisms and sequencing of flooding in HPW 26

Figure 2-16 Areas with groundwater flooding when river levels are high, prior to a flood-inducing rainfall event (areas of black stippling) 27

Figure 2-17 Flooding in the initial period following a significantly high period of rainfall (additional green stippling to Figure 2.16) 28

Figure 2-18 Areas indicating more serious flooding occurring (additional orange stippling to Figures 2.16 and 2.17, plus orange blocks identifying properties with basements) 29
Figure 2-19 Flooding heading towards peak levels (additional blue stippling to Figures 2.16-2.18, plus blue areas identifying key flooded roads) 30
Figure 2-20 Flood waters at peak levels experienced in past two decades (additional purple stippling to Figures 2.16-2.19) 31
Figure 3-1 Correlation coefficient for pairs of river and groundwater time series against distances of the boreholes from the nearest river 35
Figure 3-2 Lag of groundwater levels behind river levels for paired time series against distances of the boreholes from the nearest river 35
Figure 3-3 January 2003 flood: top - Rainfall at EA rain gauges within the Upper Thames, Evenlode and Cherwell catchments; bottom – hydrographs from river stations upstream of and within the Oxford floodplain 39
Figure 3-4 July 2007 flood: top - Rainfall at EA rain gauges within the Upper Thames, Evenlode and Cherwell catchments; bottom – hydrographs from river stations upstream of and within the Oxford floodplain 40
Figure 3-5 January 2008 flood: top - Rainfall at EA rain gauges within the Upper Thames, Evenlode and Cherwell catchments; bottom – hydrographs from river stations upstream of and within the Oxford floodplain 41
Figure 3-6 November 2012 flood: top - Rainfall at EA rain gauges within the Upper Thames, Evenlode and Cherwell catchments; bottom – hydrographs from river stations upstream of and within the Oxford floodplain 42
Figure 3-7 December 2012 flood: top - Rainfall at EA rain gauges within the Upper Thames, Evenlode and Cherwell catchments; bottom – hydrographs from river stations upstream of and within the Oxford floodplain 43
Figure 3-8 Winter of 2013/14 flood: top - Rainfall at EA rain gauges within the Upper Thames, Evenlode and Cherwell catchments; bottom – hydrographs from river stations upstream of and within the Oxford floodplain 44
Figure 3-9 December 2020 flood: top - Rainfall at EA rain gauges within the Upper Thames, Evenlode and Cherwell catchments; bottom – hydrographs from river stations upstream of and within the Oxford floodplain 45
Figure 3-10 February 2021 flood: top - Rainfall at EA rain gauges within the Upper Thames, Evenlode and Cherwell catchments; bottom – hydrographs from river stations upstream of and within the Oxford floodplain 46
Figure 3-11 January 2024 flood: top - Rainfall at EA rain gauges within the Upper Thames, Evenlode and Cherwell catchments; bottom – hydrographs from river stations upstream of and within the Oxford floodplain 47
Figure 3-12 November 2024 flood: top - Rainfall at EA rain gauges within the Upper Thames, Evenlode and Cherwell catchments; bottom – hydrographs from river stations upstream of and within the Oxford floodplain 48

LIST OF TABLES

Table 3-1 Borehole/river station pairings used to analyse relationship between river levels and groundwater levels in the Oxford floodplain, with information on the overlapping time series 34

Table 3-2 Pearson Correlation Coefficients for river and groundwater level pairings and the lag of groundwater behind river level for the highest 5% and 1% of groundwater levels for each pair 34

Table 3-3 Timings of Flood Warnings and Warning Updates (along with associated Flood Alerts) issued for HPW since 2006, and their relationship to the time that flood thresholds were passed at Iffley Lock (downstream) on the River Thames and Cold Harbour on the Hinksey Stream..... 51

Table 3-4 EA river stations upstream of HPW, the minimum peak water level that coincided with the 13 major flood events in HPW since 1998 and the number of times that level was crossed without flooding occurring in HPW. The river the stations are located on, the distance from the HPW (i.e. a location on the river at HPW with the Northing of 204700m), and a description of the river station 52

Table 3-5 Lags and Pearson's Correlation Coefficients for pairs of river stations at HPW and upstream, using the highest 5% and 1% of HPW station river level data 53

1 INTRODUCTION

Project Groundwater (PG) is a six-year Defra-funded programme working with communities in high-risk flood areas in Oxfordshire, Buckinghamshire, Luton, West Berkshire and Hertfordshire. It is led by Buckinghamshire Council in partnership with local authorities and Flood Community Groups. The programme aims to drive innovation in flood and coastal resilience and adaptation to a changing climate, specifically transforming how communities prepare and respond to groundwater flooding. Although much of the focus of the project is Chalk groundwater flooding, it is also assessing Permeable Superficial Deposit (PSD) groundwater flooding. PSD groundwater flooding occurs as a result of abnormally high groundwater levels in areas that are underlain by shallow unconsolidated aquifers. The high groundwater is primarily driven by levels in rivers in good hydraulic connection with the same shallow aquifers.

Management of flood risk in areas prone to PSD groundwater flooding in England is challenging. This report explores the appropriateness and viability of early flood warning for these areas, focussing on a data-rich case study. The groundwater monitoring infrastructure adopted for groundwater flood warning in Chalk areas in England was in place as a consequence of previous use for water supply. This infrastructure rarely exists in floodplain areas where PSD is an issue. Drilling of new boreholes for monitoring may be relatively inexpensive in shallow unconsolidated aquifers but finding suitable locations and an organisation to manage these can be difficult: the EA is not keen to expand its monitoring network, and local groundwater flood risk is not formally within their remit; local lead flood authorities rarely have the capacity; and local flood groups may not have the capacity or the financial resources. However, given the strong link between PSD groundwater flooding and adjacent river levels, there may be an opportunity to use the comprehensive river level monitoring network as a means to provide warning of floods with a strong groundwater component.

In the context of PSD groundwater flooding, PG has not set out to develop an operational warning system for communities, as has been possible for those in Chalk settings. The objective is to explore the options that might be effective in PSD settings and provide advice to the EA and LLFAs. Within PG there are three focus communities (Hinksey Park, Marlow and Colnbrook with Poyle) that have been identified as being prone to PSD groundwater flooding. A substantial amount of research has been undertaken on groundwater flooding in Hinksey Park Ward (HPW) in the past, by the British Geological Survey (BGS) and in relation to the Oxford Flood Alleviation Scheme, which is in development. The approach being taken by PG to assess the opportunities and constraints for managing PSD groundwater flood risk is to investigate methods for mapping the hazard and explore the viability of groundwater flood early warning. In undertaking this assessment an in-depth study has been undertaken of HPW and the insights considered for wider application.

This report is focussed on the monitoring and early warning aspects of the project specifically in relation to HPW. The initial task documented here in Chapter 2 was the collation of relevant information to allow a conceptual understanding to be developed of the flooding mechanisms within HPW. The report then in Chapter 3 addresses the investigation undertaken within HPW relating to flood early warning. In Chapter 4 the generic insights from the study of HPW are drawn out and challenges in implementing early warning more widely are explored.

Groundwater flooding cannot be addressed in isolation, especially in floodplain settings prone to PSD groundwater flooding. Flood events will involve a complex spatiotemporal mix of both groundwater

and fluvial flooding. The investigation of flood early warning documented here for HPW looks at flooding holistically. Specifically, the objectives are to:

- assess the correlation between river levels and groundwater levels within HPW;
- identify local river level thresholds that result in groundwater flooding in HPW;
- explore how local river levels relate to rainfall and river levels upstream; and
- bring all of this information together to investigate whether live data from upstream river stations could be used in an early warning for flooding in HPW.

2 CONCEPTUAL MODEL

2.1 INTRODUCTION TO CONCEPTUAL MODELLING

HPW is located to the south of the centre of the City of Oxford, primarily to the south and west of the River Thames and to the east of Hinksey Stream (Figure 2.1); it incorporates the areas of Grandpont, New Hinksey and Cold Harbour and is more commonly referred to as South Oxford. The Ward has an area of 2.35 km^2 and the population at the time of the 2021 Census was 5,578. There are approximately 2,600 properties in the Ward, the majority of which are domestic. The whole of the area sits on the alluvial deposits of the current River Thames floodplain.

The conceptualisation of flood mechanisms within HPW developed here addresses both fluvial and groundwater flooding. The flood conceptualisation is based on data and local experience of flooding in the area since 1998; prior to this period, within the accessible monitoring record, there were no significant flood events and limited experience of flooding within the community. Use is also made of river level data within and upstream of the area for the period 1998-2025 and limited groundwater level data within the area for 2003-2014. Since 1998 there have been a number of significant flood events that have included groundwater flooding within the urban area. These recent events have shown there to be a typical pattern to overall flooding although with some variability based on driving rainfall amounts and distribution on the upstream catchments.

This chapter initially provides an overview of the data sources used in developing the conceptual model, and then contextual information on the area, primarily the hydrogeology and hydrology but also an overview of flood receptors and known impacts, followed by the conceptualisation of flooding, and lastly an assessment of the knowledge gaps.

2.2 INFORMATION AND DATA SOURCES

2.2.1 National hydrometeorological monitoring network and spatial mapping

Data from the Environment Agency (EA) hydrometeorological monitoring network contributed to the development of the conceptual flood model for HPW. These include river water level and flow, and rainfall data. Stations are both local to HPW and in the catchments upstream (Figure 2.2). The data were used to understand the response of the river levels in the HPW area to rainfall events in the catchments of the Thames and the feeder catchments of the Rivers Evenlode and Cherwell. Although some gaps exist, water level data available were generally on a sub-hourly frequency. Water levels were averaged on an hourly basis for flood event analysis.

In addition to hydrometeorological data, spatial mapping was also used within the conceptual modelling. High resolution topographic data (1m resolution) are available for Oxford surveyed through

the EA National LiDAR Programme (Figure 2.3). Geological bedrock and superficial deposits maps of the area are available at 1:50,000 scale from BGS (Figure 2.4).

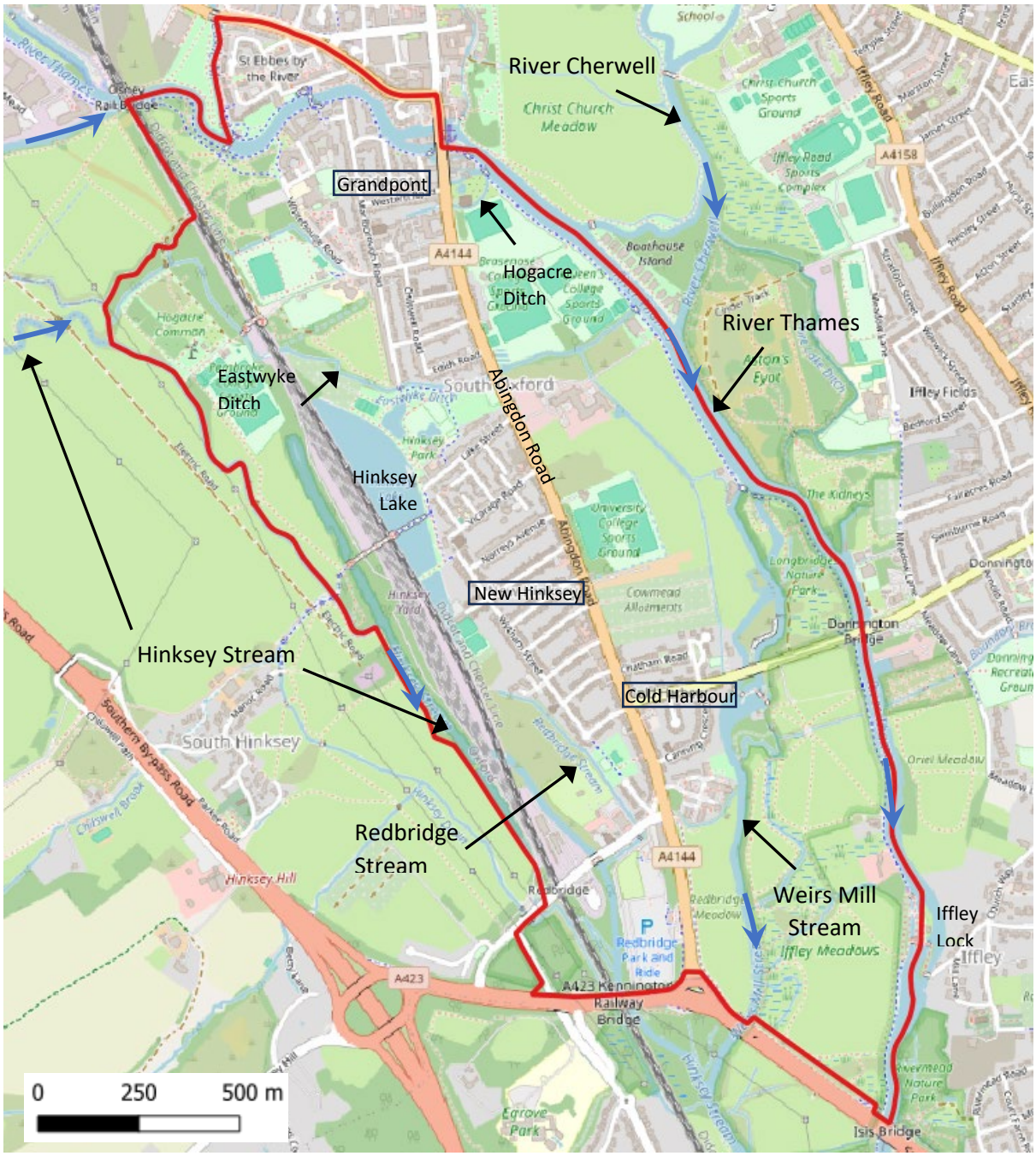
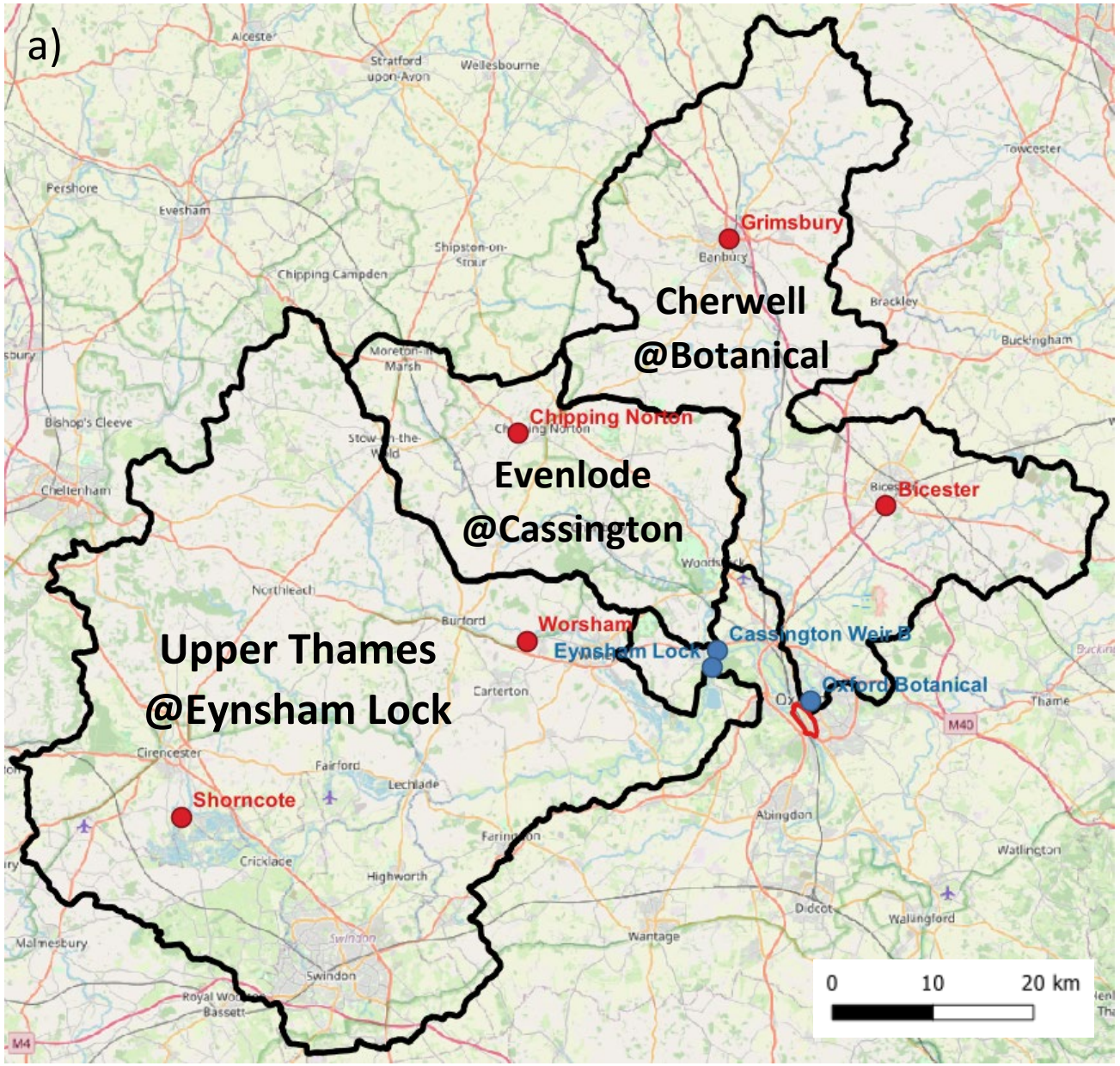
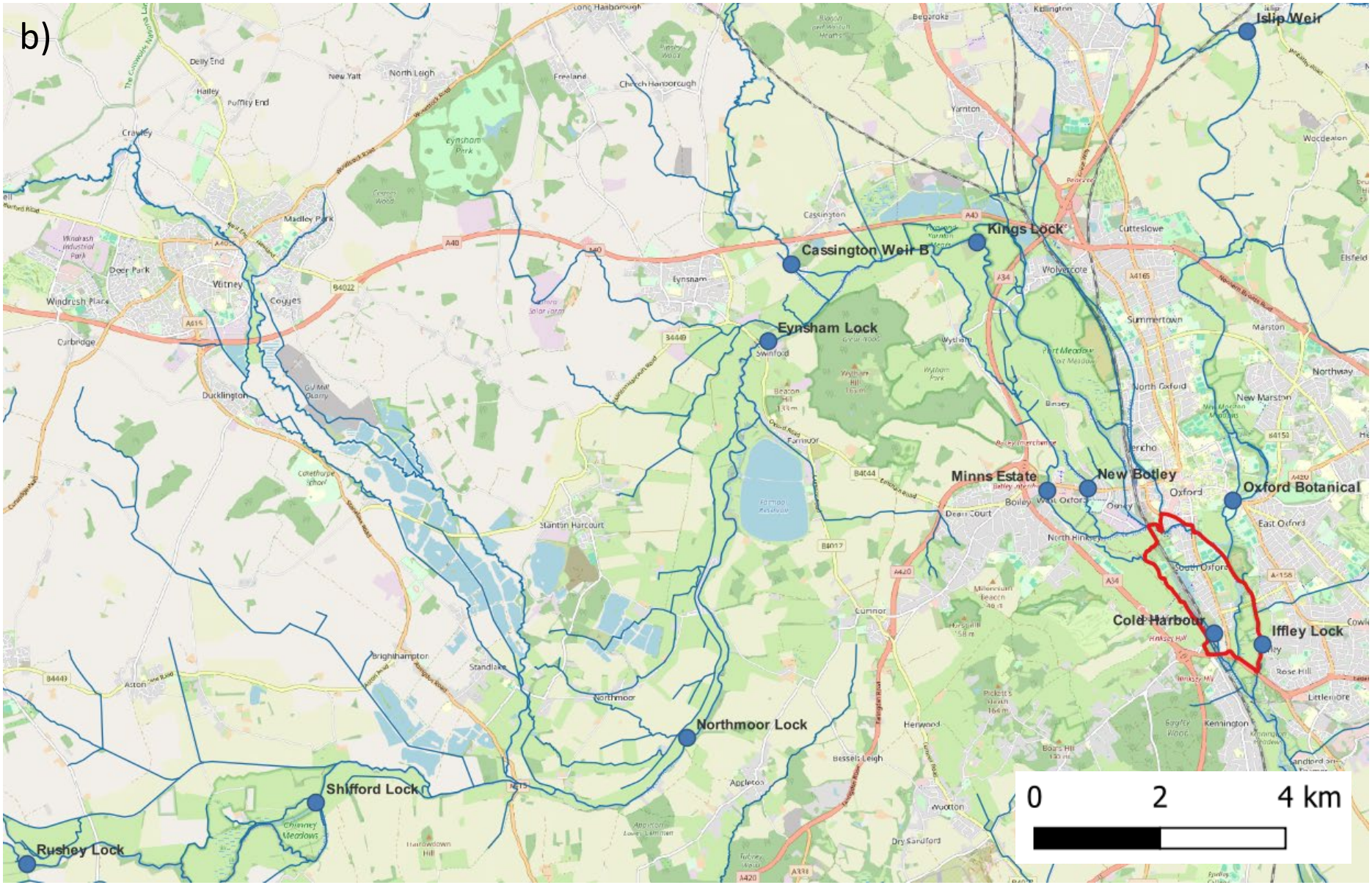


Figure 2-1 Hinksey Park Ward (red polygon), the boundary for the Project Groundwater community. Blue arrows show direction of river/stream flow.


a)
Grimsbury
Cherwell
@Botanical
Chipping Norton
Evenlode
@Cassington
Bicester
Worsham
Eynsham Lock
Cassington Weir B
Oxford Botanical
Upper Thames
@Eynsham Lock
Shorncote
0
10
20 km


b)
Islip Weir
Kings Lock
Cassington Weir B
Eynsham Lock
Minns Estate
New Botley
Oxford Botanical
Cold Harbour
Iffley Lock
Northmoor Lock
Shifford Lock
Rushey Lock
0
2
4 km

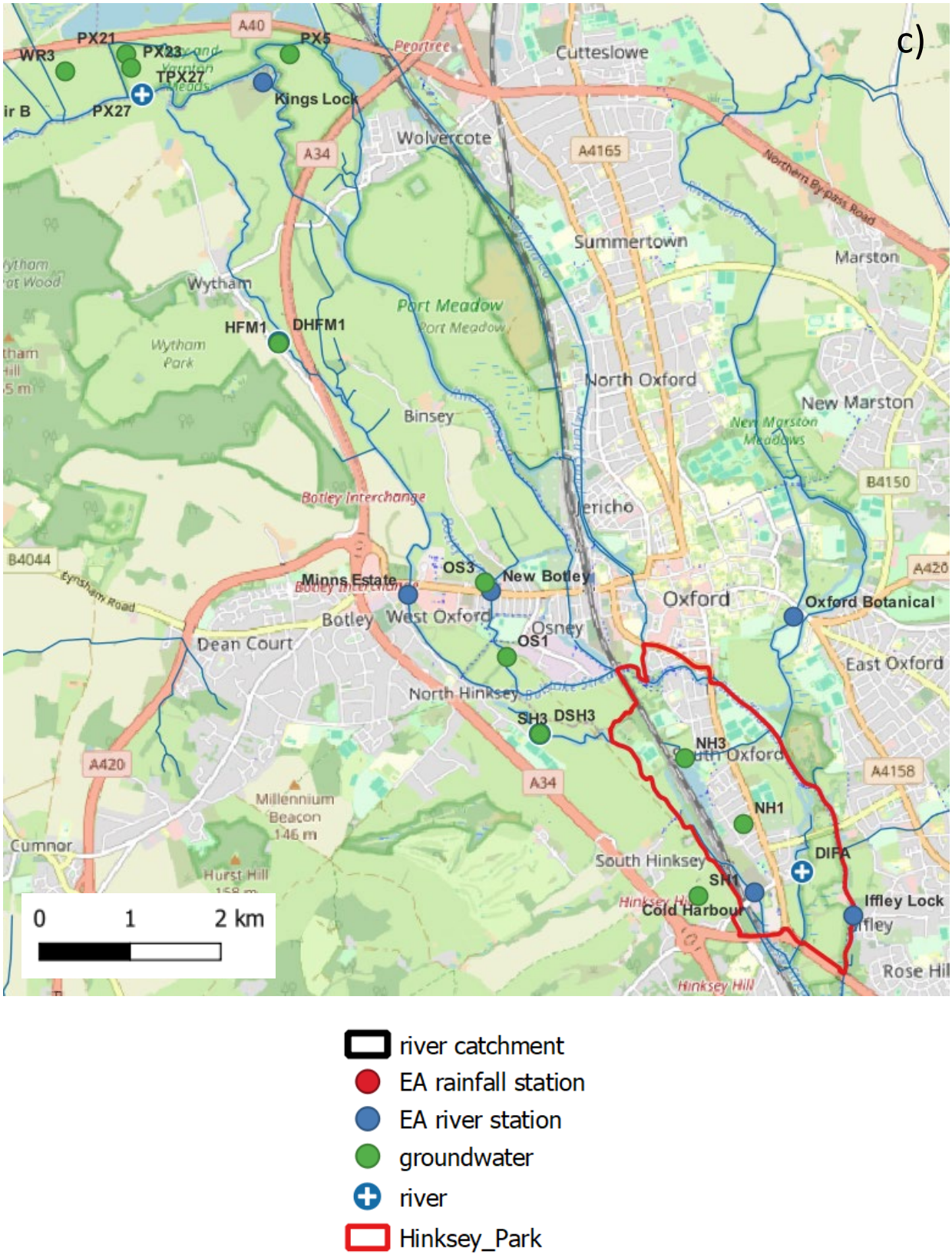


Figure 2-2 *a) River catchments and EA rainfall stations; b) EA river stations referred to in report; c) EA river stations within the Oxford floodplain, and groundwater and river monitoring sites used within analysis included in report*

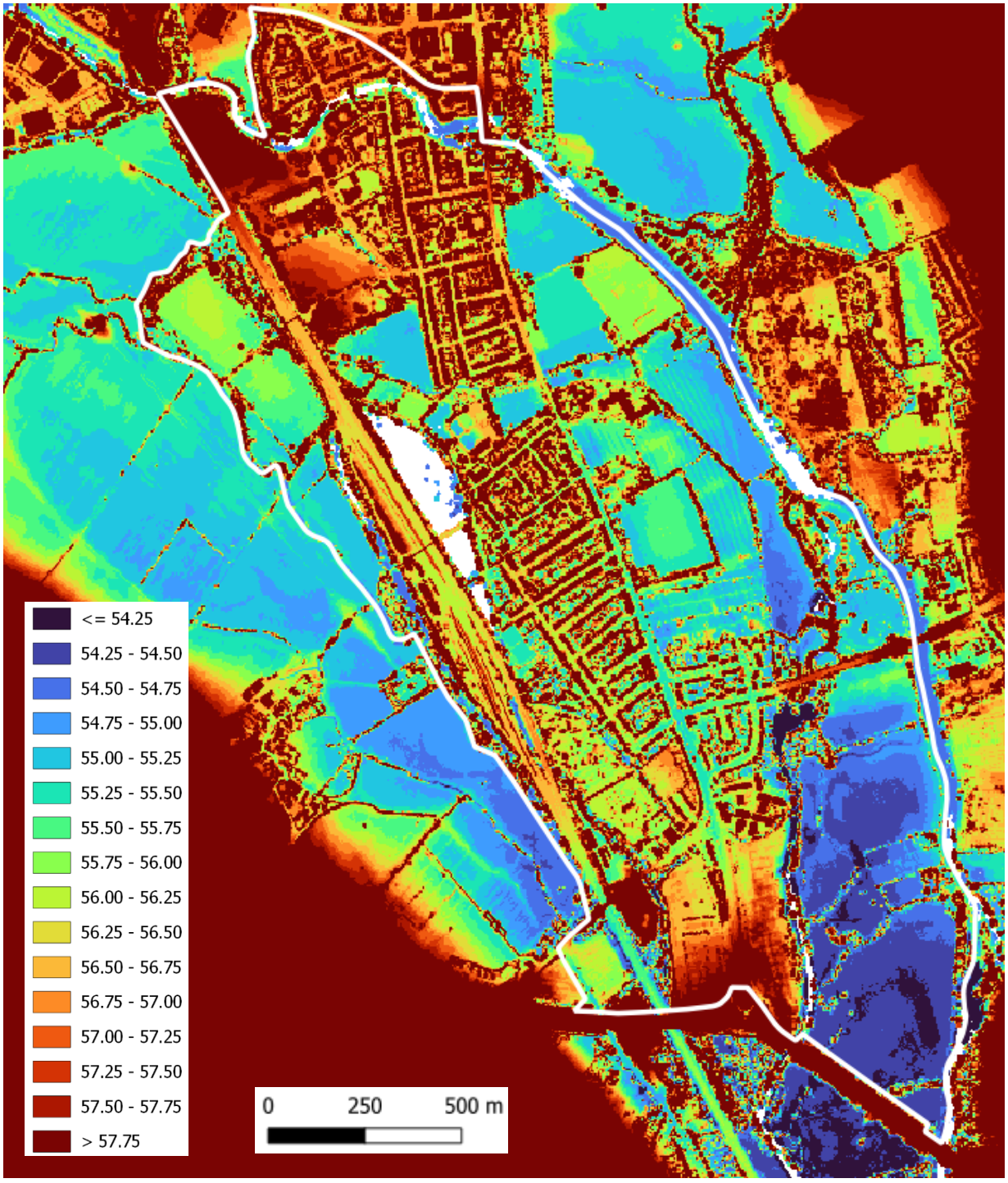


Figure 2-3 LiDaR elevation in mAOD for HPW (white polygon)

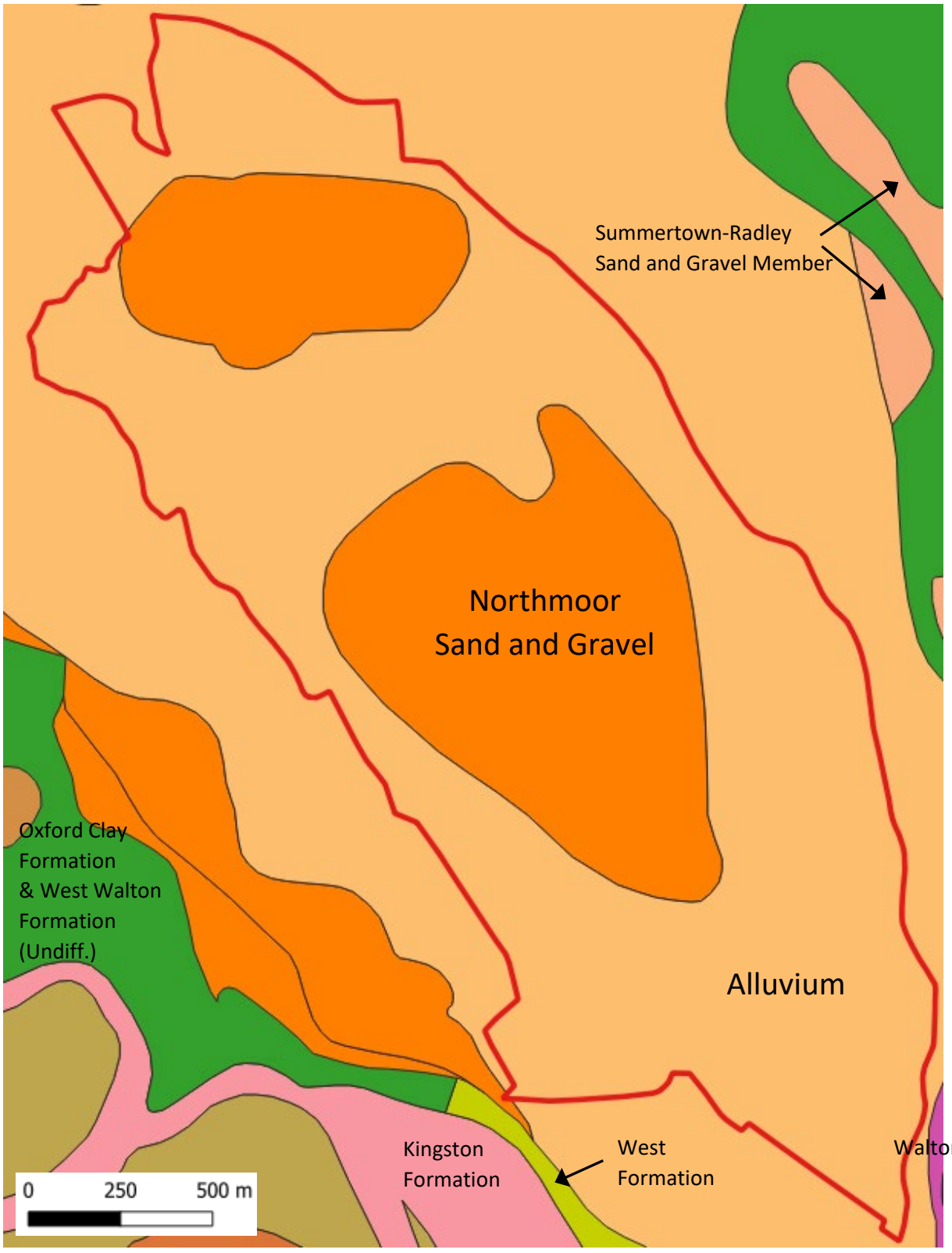


Figure 2-4 1:50K bedrock and superficial geology for HPW area

2.2.2 Local flood-related studies

Extensive work has been undertaken on flooding in the South Oxford area, both fluvial and groundwater flooding, as part of research on the urbanised floodplain area of Oxford and in relation to current and past studies as part of the development of a flood alleviation scheme for Oxford. Much of this work has focussed on HPW. The following initiatives have resulted in the collection of data relevant to surface water and groundwater flows.

Oxford Flood Risk Management Strategy (OFRMS): this study was commissioned by the EA in 2002 and led by the consultants Black & Veatch. The study reported in 2009, establishing a phased plan of short-term defences, medium-term structural solutions, and long-term upstream storage. The OFRMS involved the development of a network of boreholes and stilling wells to monitor groundwater and surface water levels, as well as the collation and analysis of data from the EA's established network. The drilling of monitoring boreholes added to the understanding of the nature and thicknesses of the superficial deposits within the current floodplain of the Thames. The groundwater data collected were databased and analysed through a joint project with BGS. Outputs from the OFRMS included a hydrogeological review (B&V, 2009) and river modelling (EA, 2009) that were the basis of the option assessment that was a component of the OFRMS.

Research projects within the Oxford Thames Floodplain: between 1984 and 2024 a series of research projects were undertaken within the floodplain of the River Thames in the Oxford area. These addressed a range of objectives: overview of hydrological processes within the floodplain (Dixon, 2004; Macdonald et al., 2018); influence of gravel extraction (Dixon et al., 1990) and drought-related river water abstraction on ecologically-sensitive habitats (Gowing and Youngs, 2005); the impact of legacy landfills on groundwater and river water quality (Gooddy et al., 2014); and the mechanisms and risks associated with groundwater flooding (Macdonald et al., 2012). These research projects were undertaken by institutes including BGS, the Institute of Hydrology (now the UK Centre for Ecology and Hydrology), and Cranfield University. As part of these projects, activities undertaken included: the installation and monitoring of boreholes and stilling wells; the quantification of hydrogeological properties; and the 3D mapping of superficial deposits. Although these projects primarily addressed northern areas of the Oxford floodplain, the groundwater flood research focussed on South Oxford. Analysis of these data allowed the interaction of groundwater and surface water to be better understood, including during periods of flooding. There was some overlap between this research and the activities of the OFRMS.

Oxford Flood Alleviation Scheme (OFAS): the medium-term solution proposed through the OFRMS was not acted upon initially but, as a consequence of further significant flooding in Oxford, a new study was initiated in 2014 that has resulted in the development of a flood alleviation scheme that is currently at planning stage. The OFAS has involved further data being collected through new and existing monitoring infrastructure for surface and groundwater. Groundwater and river modelling has been undertaken to help define the nature and effectiveness of options for flood risk reduction.

The information and data outlined here will be referenced in the subsequent section describing the physical setting of HPW.

2.2.3 Local flood impact data

Documented data on the impact of flooding within HPW are limited. A report was published in 2003 by the OFRMS on collated information obtained from 461 completed questionnaires across Oxford (from 3,664 issued to properties within the Oxford floodplain) relating to impacts of the December 2000 flood (EA, 2003). This included overviews and summaries of responses to individual questionnaires for Grandpont and New Hinksey (which included Cold Harbour) areas.

No Section 19 flood investigation reports (as required by the Flood and Water Management Act 2010) could be found for HPW. A list of Flood incidents for Oxford City was received from Oxfordshire County Council in 2021 which included two reports of internal flooding in February 2021 in HPW.

The greatest insights into flood impact in HPW have come through direct observations by the author of this report and discussions held with other local residents over the period since December 2000.

2.3 CONTEXTUAL INFORMATION

2.3.1 Physical features, including surface water network

The majority of the urban area of HPW lies within the vicinity of the Abingdon Road, one of the major highways into Oxford (Figure 2.1). The road crosses the River Thames at Folly Bridge. A small area of the Ward, St Ebbes by the River, sits to the north of the River Thames. The main north-south railway line runs approximately parallel to the Abingdon Road. Over half of the area of the Ward is vegetation at or close to the level of the natural floodplain. This includes: sports playing fields belonging to the City Council and University of Oxford colleges; the Iffley Meadows SSSI in the south, and other meadows and nature and public parks; allotments and scrub ground; and domestic gardens (Figure 2.1).

Figure 2.3 is a map of the elevation of the area, created from high resolution topographical mapping using LiDaR sensors (Light Detection and Ranging). This map highlights how roads, railway and buildings were built up from the natural floodplain, with the recognition at the time of construction that the land was prone to flooding. This is also shown in the map of thickness of made ground above the natural floodplain (Figure 2.5), reproduced from Macdonald et al. (2012), which also identifies highs in ground elevation due to historic waste dumps.

Figure 2.1 highlights the complex hydrological setting of Hinksey Park, with rivers forming its boundary on all sides and rivers and ditches crossing through. The River Thames is the primary river in the area. Its source is in the Cotswold Hills to the west of Oxford (Figure 2.2). The river is fed by tributaries such as the River Windrush and the River Evenlode, the latter joining just before the Thames turns to the south and passes through Oxford. The River Cherwell joins the Thames to the south of Oxford city centre. The Hinksey Stream, which flows to the west of HPW originates as the Seacourt Stream which receives its flow via a fixed weir from the River Thames just downstream of the confluence with the River Evenlode. The Hinksey Stream rejoins the River Thames south of HPW where it then flows through a narrow gap in the surrounding hills (see below).

The main channel of the River Thames cuts through the northern end of HPW and then forms its eastern boundary. Iffley Lock is located on the River Thames further downstream on this eastern boundary (Figure 2.1). During non-flood conditions the river level drop from upstream to downstream of Iffley Lock is typically ~80cm. The Thames channel bifurcates approximately 1.1 km upstream of Iffley Lock, forming the Weirs Mill Stream, which eventually joins back up with the Thames approximately 0.9 km downstream of Iffley Lock. The Weirs Mill Stream has a series of weirs along its course.

The Hinksey Stream forms much of the western boundary of HPW. This has only one minor stream management structure on it, in the Redbridge area, with a drop of a few tens of centimetres. The Redbridge Stream bypasses this structure to the east. Two named ditches passing west-east link the Hinksey Stream to the River Thames: the Eastwyke Ditch and Hogacre Ditch. The Eastwyke Ditch is the larger of these two and flows throughout the year; it flows towards the Thames in higher flow periods but can reverse during low flows. East of the Abingdon Road an unnamed ditch runs from the Eastwyke

Ditch parallel to the River Thames, joining up with the Weirs Mill Stream. This is dry for much of the year but becomes a significant flow path during periods of flooding. The Hogacre Ditch is partly culverted within the Grandpont urban area. The Hinksey Stream flows south under the city's southern bypass. Restrictions on the downstream movement of water associated with the Hinksey Stream during high flows is considered one of the causes of flooding and a focus of measures to reduce flood risk within the OFAS.

Hinksey Lakes are located to the west of the New Hinksey area and the east of the railway line (Figure 2.1). These were created by extraction of gravel to build past and current railways. The lakes are formed by groundwater. The larger northern lake is separated by a berm from the smaller southern lake; it has no surface water inflows. Anecdotal information suggests there is a conduit from the northern to the southern lake through the berm although possibly blocked by sediment and debris. There is a conduit linking the southern lake to the Redbridge Stream which flows during periods when the lake level is relatively high. During the initial periods of flooding water backed up due to the southern bypass flows north back through the conduit into the lake. Additional narrow lakes formed by gravel extraction run parallel to the railway to its west.

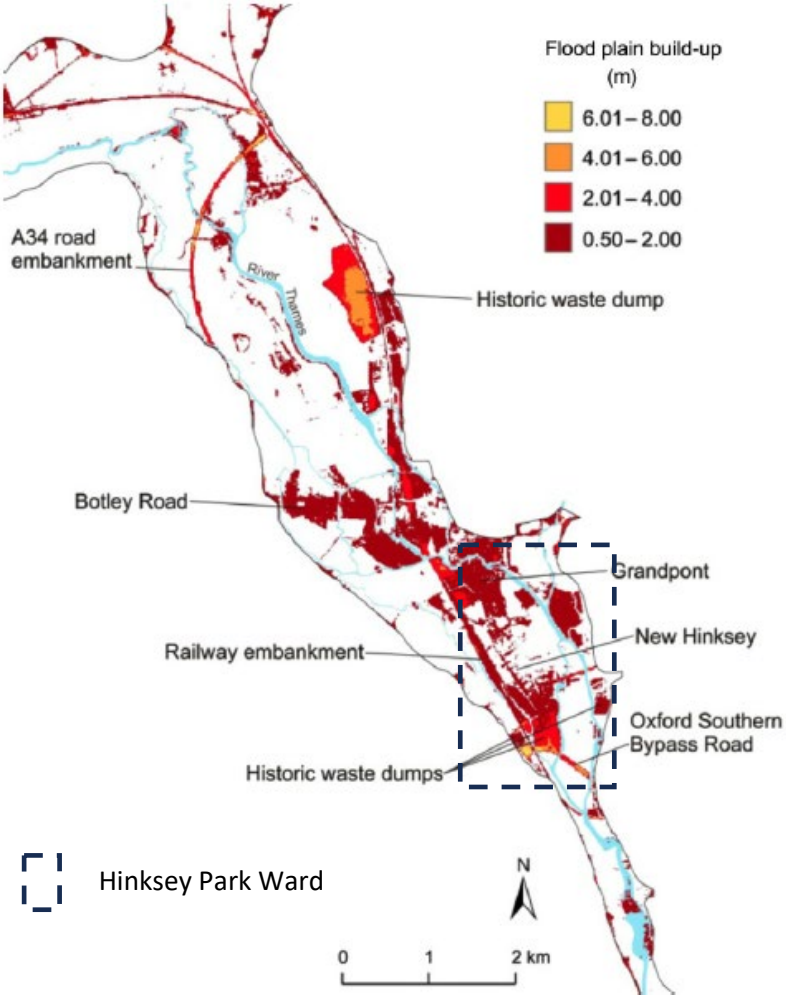


Figure 2-5 Thickness of made ground above the natural flood plain (from Macdonald et al., 2012). The areas of Grandpont, New Hinksey and Cold Harbour are indicated. HPW is enclosed within the dashed box

2.3.2 Geology and hydrogeology

The BGS has mapped the bedrock geology underlying HPW as poorly permeable mudstone of the Oxford Clay and West Walton Formations (Figure 2.4). Superficial deposits on top of the bedrock consist of sands and gravels of the Northmoor Terrace overlain by alluvium; these are associated with the modern floodplain. The alluvium is mostly a fine-grained deposit of dark silt, or silty clay with thin beds of peat and lenses of gravel and sand (Newell, 2008). Although the alluvium is not shown as present across the whole of HPW, BGS only maps the geology from a depth of approximately one metre and it is considered that alluvium overlies all of the gravels. A contour map produced by Newell (2008) from a 3D geological model based on borehole logs held by BGS (see Figure 2.6), shows typical alluvium thicknesses in the southern part of the Oxford floodplain of 1-2 metres. A companion contour map of the thickness of the Northmoor Terrace gravels (Figure 2.6) shows a significant depth of gravels of ~8m in the vicinity of the Hinksey Stream to the west of HPW. Minimum depths of gravel towards the east of the area are around 2m. The width of the superficial deposits across the floodplain in the area of HPW is ~2.1 km; this narrows to less than 500 m as the river flows through the more competent bedrock of the Corallian Group that forms the high ground to the west and east of the floodplain. The extent of the superficial deposits reduces as the floodplain narrows.

Movement of groundwater through the bedrock mudstones that underlie the superficial deposits is likely to be insignificant in the context of the local water balance (Schofield et al., 2014). Dixon (2004) reports hydraulic conductivities (K) for the Northmoor Terrace gravels across the whole of the Thames floodplain in Oxford, based on pumping and packer tests, to be in the range 100 to 1000 m/d, high even for gravels. Gooddy et al. (2014) calculated the gravel K range to be 200 to 600 m/d based on grain size distribution in the Port Meadow area. Values for the gravel K are limited in the south of Oxford but, where available, are also high, with values calculated by BGS using grain size distribution at two locations as 117 and 270 m/d at depths of 3-4 metres. In contrast, Ks for the alluvium estimated in a number of studies undertaken in the Oxford valley, including in HPW, are substantially lower, ranging from 0.03 to 0.3 m/d (Gardner, 1991; Gowing & Youngs, 2005; Hodgson, 2008).

Dixon (2004) suggests storage coefficients, derived from pumping tests in the gravels of the Oxford floodplain, typically indicate confined or semi-confined conditions (e.g. 1.5×10^{-5} beneath Yarnton Mead in the north of the floodplain, where the confining alluvium is on average 1.8 m thick).

2.3.3 Hydrological data

2.3.3.1 Groundwater-surface water interaction

Evidence from research that has taken place within the superficial deposits of the Oxford floodplain (Macdonald et al., 2018) shows that rivers and streams are hydraulically well-connected to the adjacent aquifers, and that locks and weirs that are used to raise upstream river levels to improve navigation also influence groundwater levels across the floodplain. For example, a comparison of water level in the Hinksey Stream, just upstream of HPW (Figure 2.7a), and the groundwater level in an adjacent monitoring borehole shows how the two levels follow each other closely. This is seen at other paired sites across the floodplain although the relationship is closer at paired sites on the Seacourt and Hinksey Streams where the groundwater gradient is generally from the aquifer towards the stream. With the River Thames the hydraulic gradient outside of periods of flooding is more often from the river towards the aquifer (Figure 2.7b). It is thought that the baseflow to the streams helps to clear sediment from the bed whereas the reverse gradient within the Thames is likely to cause the build-up of finer sediments on the river bed, reducing its permeability; the paired water levels provide evidence for this hypothesis.

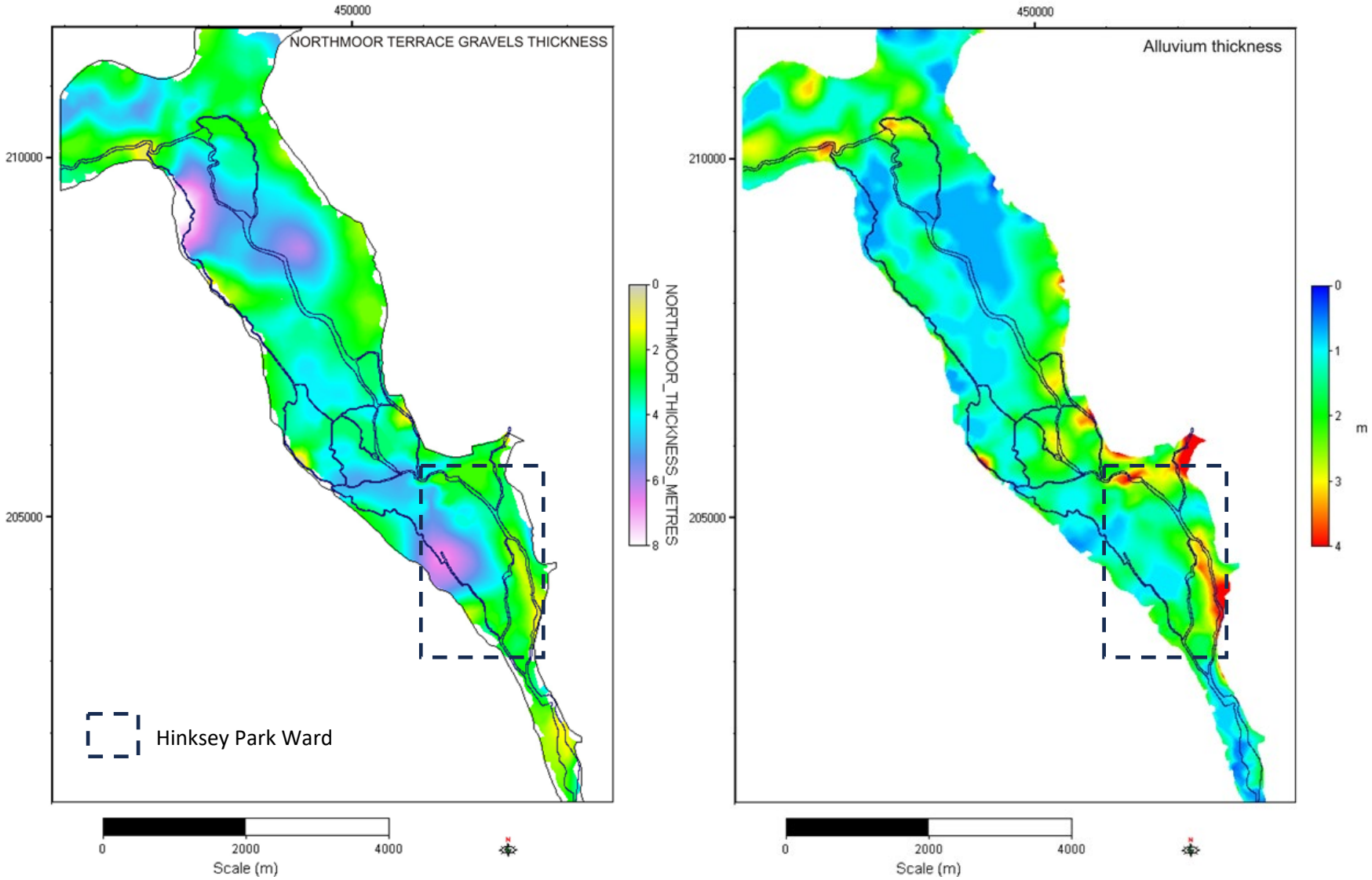


Figure 2-6 Thickness of Northmoor Sand & Gravels (left) and Alluvium (right) in the Oxford area (from Newell, 2008). HPW is enclosed within dashed box

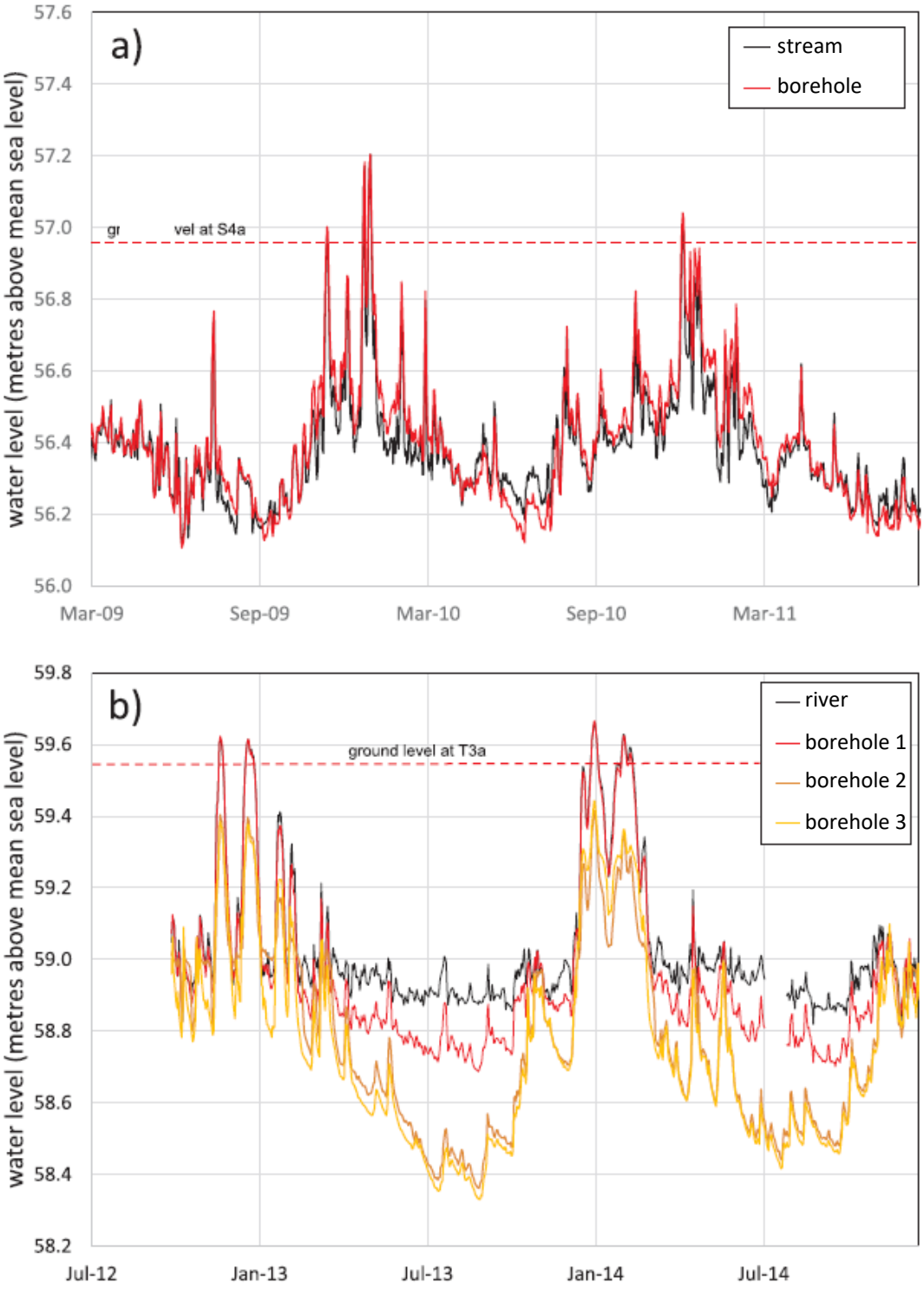


Figure 2-7 a) Seacourt Stream water level and groundwater level in a borehole completed in the sand and gravel deposits a few metres from the stream; b) River Thames water level and adjacent groundwater levels at Yarnton Mead in the northern part of the Oxford floodplain. Boreholes are a few metres (bh1), ~300 m (bh2) and ~500 m (bh3) from the River Thames. (from Macdonald et al., 2018)

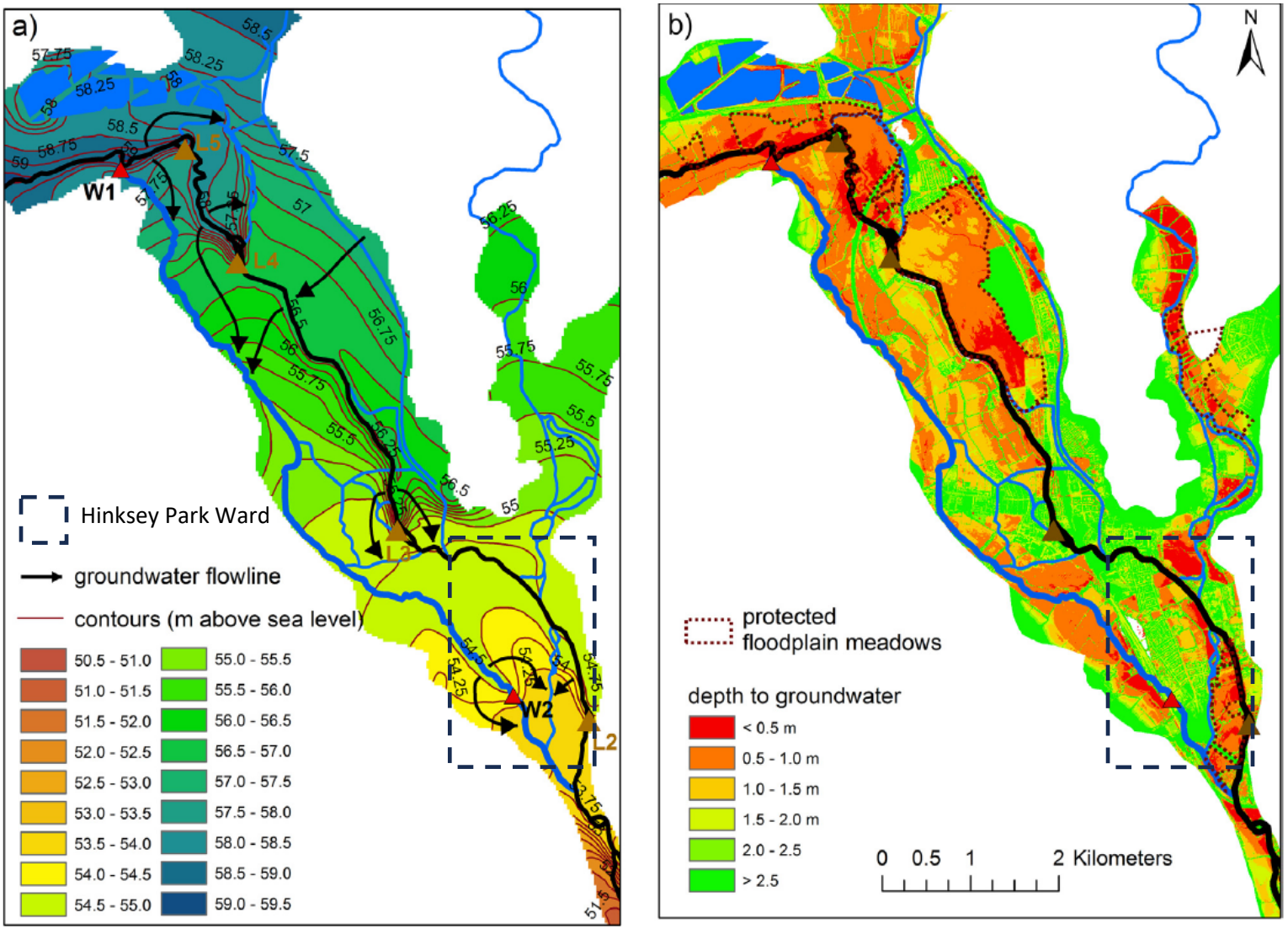


Figure 2-8 a) contoured groundwater levels and groundwater flow lines in the floodplain gravel aquifer; and b) depth to groundwater within the gravel aquifer. Both maps based on measurements in May 2007 (from Macdonald et al., 2018). HPW is enclosed within the dashed box

Using surface water and groundwater levels collected in the 2000s, from the monitoring network developed primarily through the OFRMS, it was possible to produce groundwater level contour maps for the Oxford floodplain gravel aquifer (Macdonald et al., 2018). The map for May 2007 is shown in Figure 2.8a. In HPW the influence of the River Thames upstream of Iffley Lock, and to a lesser extent of the Hinksey Stream upstream of the weir in the Redbridge area, can be seen on the adjacent groundwater levels. The Weirs Mill Stream downstream of its weirs appears to be a discharge zone for groundwater. These groundwater contours reflect average-to-low hydrological flow conditions.

Monitoring during high flow periods (that will be discussed in more detail below) show that the good hydraulic connection between the rivers and the gravel aquifer mean that when river levels rise they have an immediate impact on groundwater levels. The confined to semi-confined conditions within the gravel aquifer mean that pressure waves from river pulses during high flows events are likely to be quickly conveyed through the gravel aquifer due to high aquifer diffusivity.

2.3.3.2 Groundwater depths

The groundwater level contours produced using data from the OFRMS network have been used to map the depth to groundwater across the superficial deposits of the Thames floodplain in Oxford by subtracting groundwater levels from ground surface elevation (Figure 2.8b). Depths to groundwater of greater than 2.5 m are seen in some of areas of HPW, although this is due to the past raising of land for the building of roads and property as it was known to be prone to flooding. Those areas that reflect better the natural floodplain level have depths to groundwater of less than 1 m. This fits with the evidence that the gravel aquifer is confined or semi-confined by the more poorly permeable alluvium. However, the alluvium will have been removed in the process of digging foundations for buildings and potentially subsurface pipework for sewers, storm drains, etc, creating windows that will allow groundwater to more easily move towards the ground surface during high flow or flood periods.

2.3.3.3 Surface water levels and groundwater responses during flood periods

Based on information provided by residents, since 1998 there have been 13 flood events that have had substantial impacts on HPW and are referred to here as 'major'. Major floods are defined by those that: resulted in inundation of property above ground level; closed the Abingdon Road or heavily restricted traffic movements; caused a widespread reduction in the functioning of wastewater systems (see Section 2.3.4). All included groundwater flooding.

The approximate dates of the flood peaks were as follows:

- 11/04/1998
- 16/12/2000
- 05/01/2003
- 25/07/2007
- 19/01/2008
- 27/11/2012
- 28/12/2012
- 09/01/2014
- 09/02/2014
- 25/12/2020
- 03/02/2021
- 05/01/2024
- 29/11/2024

Surface waters

A detailed analysis of flood hydrographs is provided in Section 3.3. The analysis shows that the shapes of the river hydrographs during floods are dependent on the magnitude, intensity, distribution and season (although extent of data on this latter aspect is limited) of rainfall in the catchments of the Upper River Thames, the River Evenlode and the River Cherwell. Double-peaks are commonly seen in the flood hydrographs for Hinksey Stream due to the combination of peaks from the Upper Thames and the River Evenlode. The double peak in river level is also seen in the Thames at Iffley although usually not as well defined. This is due to the input of the River Cherwell, which like the Evenlode often peaks earlier than the Thames.

Surface water, groundwater and flood water levels in Hinksey Park

Figure 2.9 shows the groundwater level data that are available for the long-term monitored borehole (NH1) in HPW (note, see Figure 2.2 for locations of all monitoring points referenced in this Section). These groundwater level data only coincide with five periods of flooding (a short break in monitoring in January 2008 coincided with a flood event). The water level data from the HPW area are shown for two of these flood events in July 2007 and November 2012 in Figures 2.10 and 2.11. These plots use DSH3, the surface water monitoring station on the Hinksey Stream operated through the OFRMS and BGS, as this had the local datum measured accurately relative to Ordnance Datum, allowing the relative elevations of water levels to be seen. The plots also include an OFRMS station on the Weirs Mill Stream downstream of the weirs, DIFA, as well as data collected by the EA from the upstream side of Iffley Lock on the Thames.

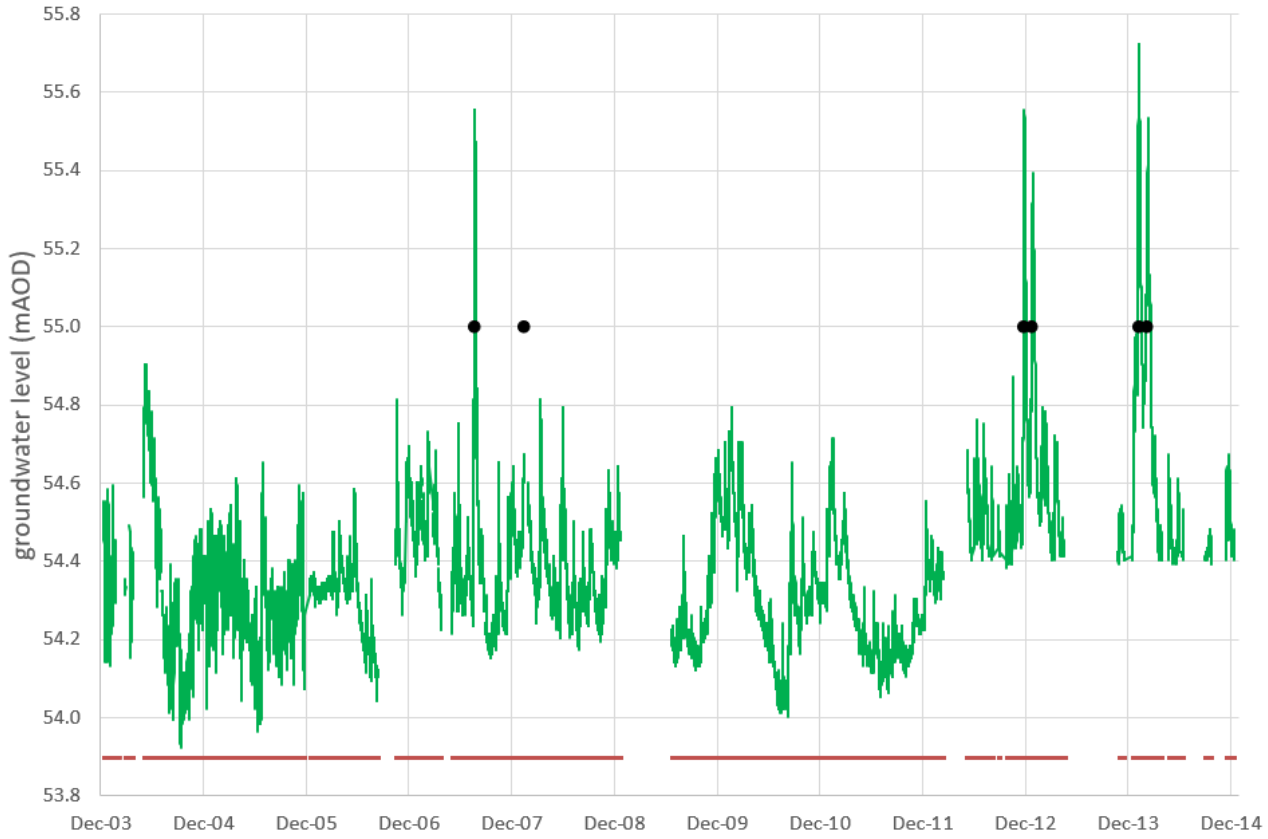


Figure 2-9 Most complete groundwater level time series dataset available for HPW, from borehole NH1, as well as timings of major flood events for this period (black dots). Red line indicates the periods for which data are available. Note, from 2012 onwards the sensor was positioned at a depth that meant it did not capture groundwater levels with an elevation below approx. 54.4 mAOD

In both plots, the data from the initial period prior to the start of the flood event illustrate the comments made earlier about the river/stream levels within HPW: the similarity in levels in the Hinksey Stream and River Thames on the two boundaries; and the Weirs Mill Stream as a groundwater sink.

The following insights can be made from the two hydrographs:

- groundwater levels appear to respond to direct rainfall initially, in particular to the intense rainfall that affected Oxford at the start of the July 2007 flood event, but then recess or stabilise after the rainfall event prior to subsequently rising in response to increased river levels;
- there is a good correlation between the shape of the Hinksey Stream and groundwater hydrographs, most notable in July 2007, that highlights the influence that the stream level has on groundwater;
- there is an approximate 21-hour delay between the peaks in the Hinksey Stream level at the Minns Estate and the groundwater level borehole in New Hinksey in both July 2007 and November 2012;

- the groundwater level at NH1 is above ground level for 2 days and 20 hours and 3 days and 19 hours, reaching peaks of 55.49 and 55.55 mAOD, in July 2007 and November 2012 respectively.

Note, direct fluvial flooding did not reach the area around the NH1 during any of the major flood events.

Due to the low permeability alluvium, the piezometric head measured by a borehole completed in the gravel aquifer does not necessarily equate to level of surface flooding caused by the groundwater. In the July 2007 event a pressure sensor was located on the ground surface in the proximity of the NH1 borehole. The groundwater head and flood water level at the site are shown in Figure 2.12. These show that there is an upward hydraulic gradient between the aquifer and the surface flood waters during the period leading up to the flood peak and for a time after. However, as groundwater heads recede in response to receding river levels, the surface flood water level becomes greater than the groundwater head measured in the borehole. This downward hydraulic gradient persisted for a couple of days before the surface flood waters disappeared.

The hydrographs for July 2007 and November 2012 both show overall that river levels in the Hinksey Stream recess more quickly than groundwater levels at NH1 after a flood event so groundwater extends the period of flooding in HPW. Quantifying the extended period is complex given the lack of data on the variation in elevation of groundwater and of the receptors, primarily the sewerage network.

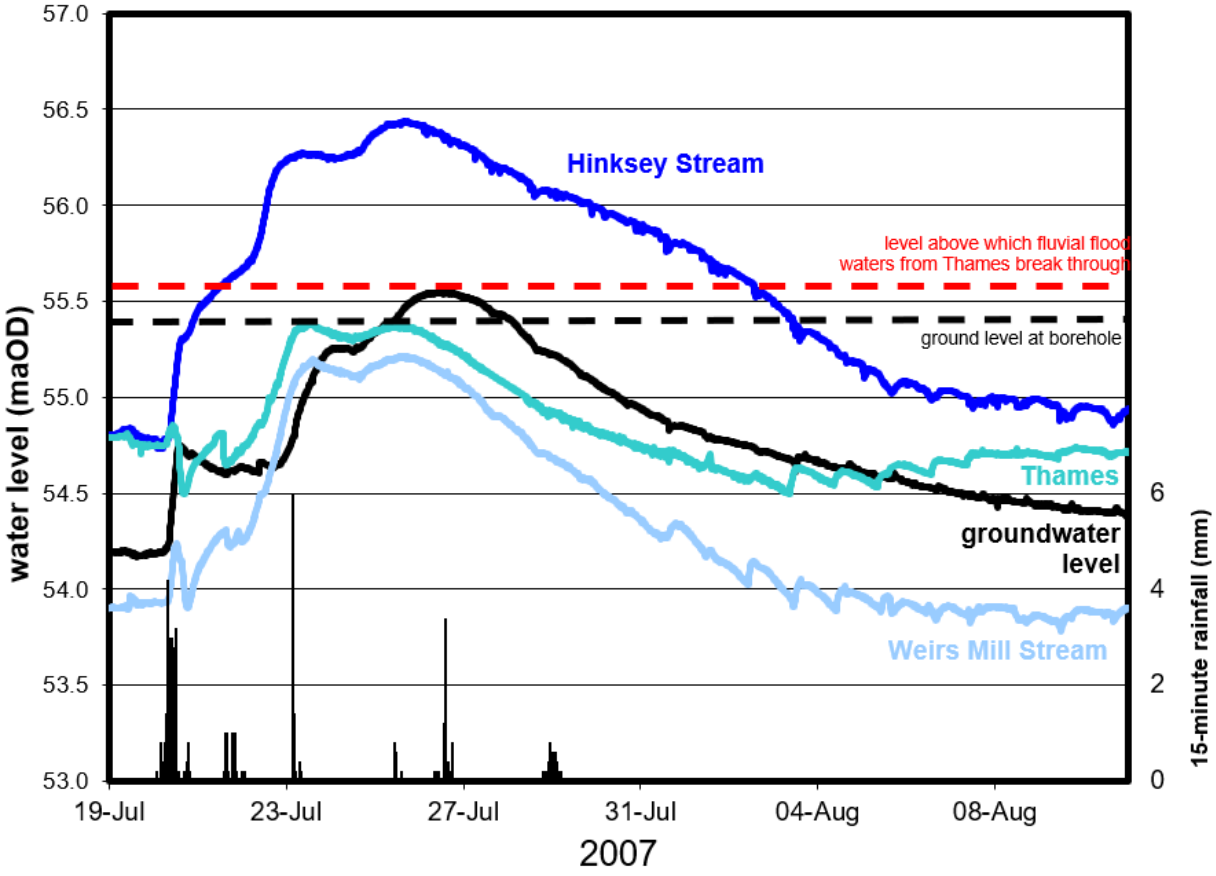


Figure 2-10 River and groundwater hydrographs for the July 2007 flood event. Note, Hinksey Stream, Thames, Weirs Mill Stream and gwl are: DSH3, Iffley Lock (upstream), DIFA and NH1 monitoring sites, respectively. See Figure 2.2 for monitoring site locations

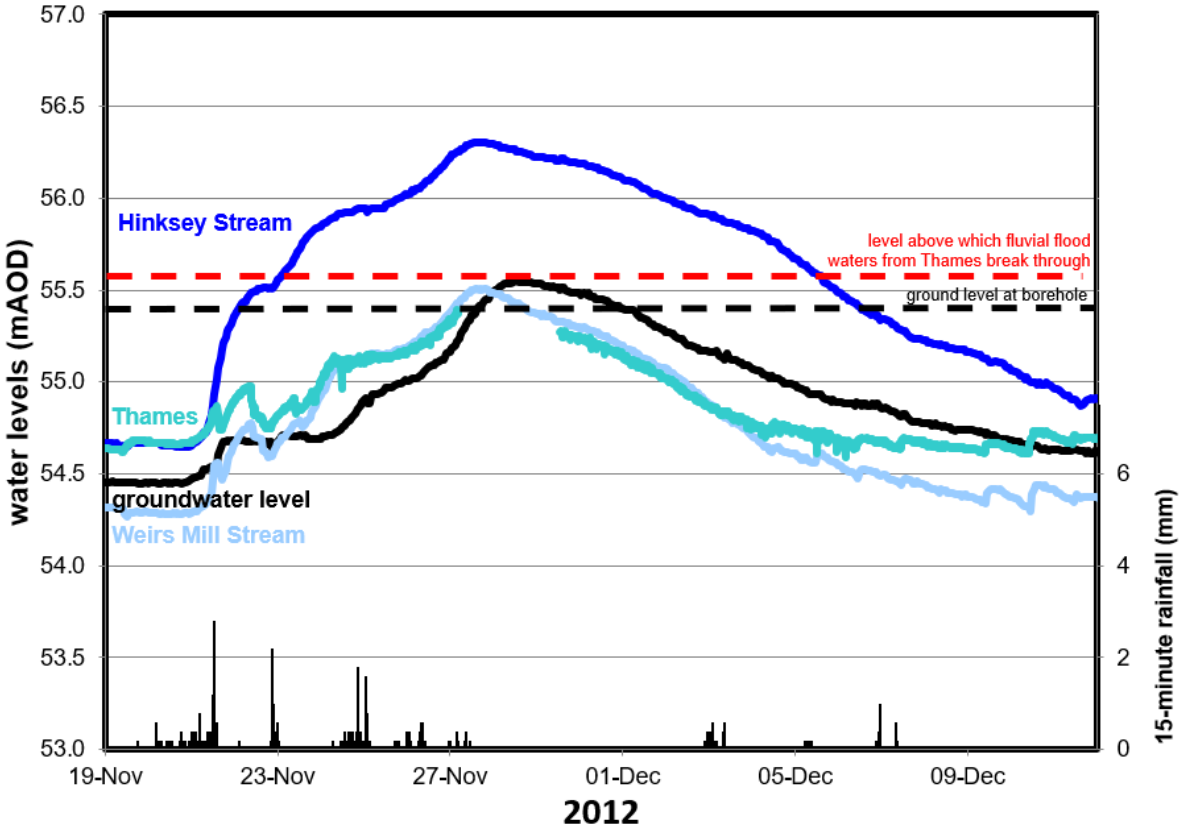


Figure 2-11 River and groundwater hydrographs for the November 2012 flood event. Hinksey Stream, Thames, Weirs Mill Stream and gwl are: DSH3, Iffley Lock (upstream), DIFA and NH1 monitoring sites, respectively. See Figure 2.2 for monitoring site locations. Note, data from Iffley Lock (upstream) are missing during the period of 27-29 November.

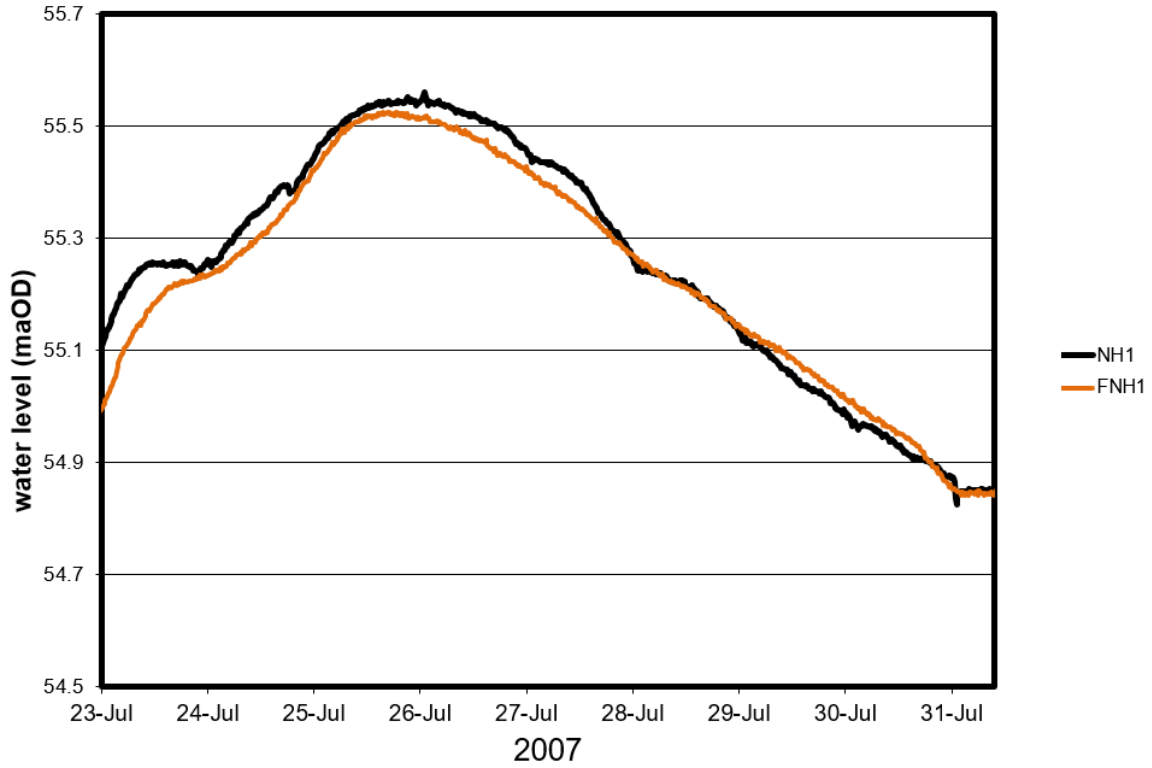


Figure 2-12 Groundwater hydrographs for borehole NH1 and ground flood water level (FNH1) in the vicinity during the July 2007 flood event

2.3.4 Flood impact and protection measures

The flood conceptualisation (Section 3.4) will describe the detail of the chronology of a typical flood event. In advance, as context, it is worth identifying the measures that have been put in place in Hinksey Park over the past two decades in response to flooding.

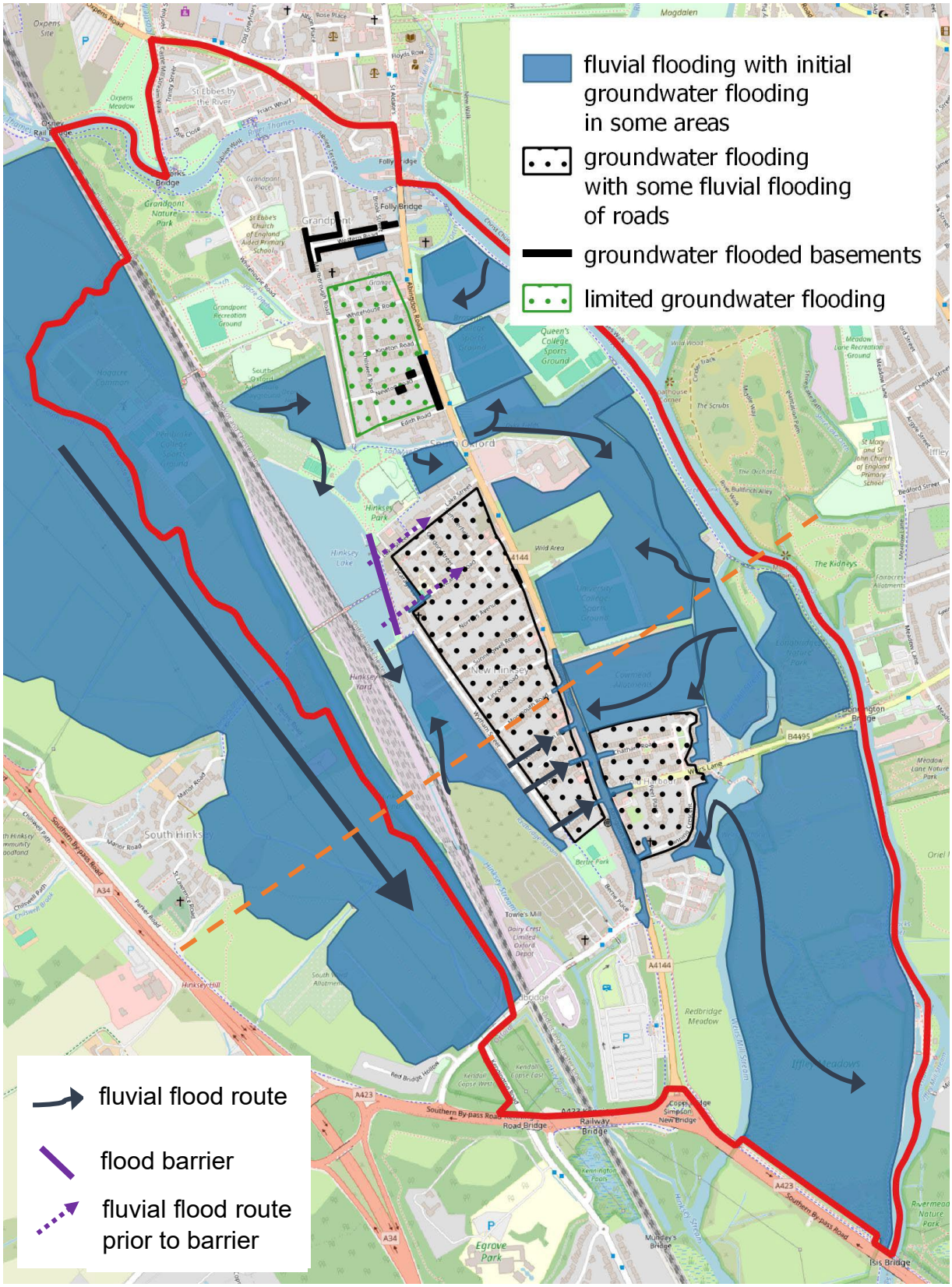


Figure 2-13 Flooded areas and flood water flow routes at the peak of a typical event in HPW (dashed orange line is the position of the vertical section shown in Figure 2.14)

2.3.4.1 Sewerage and stormwater system

Perhaps the most pervasive impact of flooding is the inundation of the sewerage system due to the ingress of groundwater as levels rise. This had a particularly significant impact in the Western Road area of Grandpont where a large number of houses had converted their basements into living areas (Figure 2.13) and where there was a backflow of sewage into these basements. Thames Water has now put pumps in place to tanker sewage from the network when it becomes overwhelmed, and residents have also installed non-backflow valves. However, there are similar issues in other areas of Grandpont that remain to be resolved.

In Cold Harbour the sewerage system is also significantly compromised during flooding, due to both groundwater and river water inflow. Oxford City Council has in the past located mobile toilets in the area for local residents. Here, and in other areas of HPW, residents have also used toilet bungs to stop the backflow of sewage. For many of those living in the area they have had to manage slowly draining toilets during the peaks of the flooding.

Stormwater drains appear to be both a sink for groundwater and a conduit for river waters during floods. In the latter case, flood water that would not otherwise be able to flow from the west to the east of New Hinksey, due to the build-up of buildings and roads above the natural floodplain level, are able to find a pathway through stormwater drains that would normally drain into the Hinksey Stream network.

It is thought that both the sewerage and the storm water drains also inadvertently act as a network to help lower groundwater level as floods recess. However, it is possible that this flow helps to maintain flood water levels in some low-lying discharge zones such as the Abingdon Road/Weirs Lane junction.

2.3.4.2 Basement flooding

The majority of Hinksey Park Ward urban construction was built up from the natural ground level as it was known that the area is prone to flooding. With some houses the height of the ground floor was sufficiently high above ground level that the void resulting beneath could subsequently be converted into a living space. These conversions were generally undertaken during the period prior to 2000 when flood events were less frequent. A survey by BGS identified ~100 properties with basements, primarily in Grandpont. Although the groundwater level drawdown that can be achieved from household pumps in very permeable gravels is limited, there are a number of properties that have installed these in sumps in their basements. In some cases the flow rate is enough to avoid groundwater inundation or at least to reduce the impact to manageable levels.

Where properties have not converted the voids beneath their ground floors, there have still been issues with electrical systems where groundwater has caused short-circuits. Impacts on the electricity network located on public land have also occurred.

2.3.4.3 Direct inundation from fluvial flood waters

During major floods the level of the Hinksey Stream rises significantly in relation to the River Thames. Flood waters from the Hinksey Stream find routes to move to the east, towards the Thames, through the urban area in particular in New Hinksey. The flow in the Eastwyke Ditch increases and water eventually overbanks and makes its way into the northern Hinksey Lake which rises to the point at which, in the past, water has overbanked and flowed eastwards through Lake Street, Vicarage Road and other roadways in the vicinity, entering properties. A barrier is now erected along the eastern bank of the northern Hinksey Lake by the EA during floods to stop this, diverting water instead to the southern Hinksey Lake. An electrical sub-station on Vicarage Road is protected additionally by a large pump operated by the City Council.

The Hinksey Stream, via the Redbridge Stream, also flows over low points in Wytham Street and makes its way eastward along roads such as Northampton Road and the southern end of Wytham Street. This affects a few properties above their ground floor. Sand bags can be helpful in these cases and some properties have installed flood barriers on doors. Water flowing west from the River Thames and the Weirs Mill Stream

upstream of the weirs does contribute to flooding in the Cold Harbour area, where groundwater flooding is also an issue. Again, resistance measures may be used where the flooding has a fluvial source.

Water that flows overland both from the Hinksey Stream and the River Thames/Weirs Mill Stream contributes to flooding of the Abingdon Road. This is one of the major impacts of the floods as it requires the Abingdon Road to be closed at the junction with Weirs Lane. This is one of the few major thoroughfares into the centre of Oxford. Closure is to avoid cars breaking down in the flood waters but also to protect houses along the flooded area of the road which are inundated by waves created by vehicles. Large pumps are used by the County Council and the Fire Service to remove water, discharging it down-gradient.

Other notable properties affected by the fluvial flood waters are: the South Oxford Bowls Club, the clubhouse of which is submerged above ground floor level by water originating from the Redbridge Stream; and the Oxford Spires, a large hotel on the eastern side of Abingdon Road, which has restricted access due to flooding from the River Thames. The high level of the River Thames also requires its towpath to be closed for safety reasons along most of the river reach bordering HPW.

2.3.4.4 Gardens and outbuildings

Gardens of many properties are affected by flooding from both fluvial and groundwater flooding. This can cause the dieback of non-flood-tolerant garden plants and the inundation of garden offices and sheds, where these have not been built taking into account flood thresholds. Community allotments are also affected by flooding but this does not generally occur during growing seasons. Residents have become more aware of raising the threshold of outbuildings and the use of flood-tolerant plants.

2.4 FLOOD CONCEPTUALISATION, MECHANISMS AND SEQUENCING

As already highlighted, flooding in HPW is complex, combining fluvial and groundwater sources. A simplified conceptualisation of the flooding is presented here, followed by a more detailed sequencing of a typical flood, along with the mechanisms occurring at each phase and areas affected. Although evidence was provided above on the variability of the river levels driving the major floods in HPW due to the amount and spatiotemporal distribution of rainfall in the river catchments, the local experience is that the floods do follow a similar pattern, so it is valid to discuss a 'typical flood'.

2.4.1 Flood conceptualisation

Figure 2.13 summarises the mechanisms of flooding in HPW and the areas that flood at the peak of the major flood events that have occurred since 1998. Data could not be found on the return periods of all the floods that have affected Oxford in this period but the July 2007, which is one of the largest floods, was estimated as a 15- to 20-year return period event (Macdonald et al., 2012). The flooding described here relates to events of this order. Note, the areas of fluvial flood inundation on Figure 2.13 are all within the High and Medium probability zones of the EA Risk of Flooding from Rivers and Sea maps.

Nearly all major floods have occurred in the late autumn or winter seasons, the significant exception being the July 2007 flood. However, typically the pre-flooding period has high river levels associated with overall wetter periods of the year that sees some persistent groundwater flooding in the lowest lying natural floodplain areas.

The major floods are initiated by relatively intense periods of rainfall; this may be a single very large rainfall event, a period of a number of days of sustained higher than normal rainfall, or a combination of both of these. This will cause the initial rise in the river level of the Hinksey Stream. The River Thames is slower to respond generally, in part because it is a larger river but also because it has locks and associated weirs to manage levels.

The rise in the Hinksey Stream level causes associated streams, such as the Redbridge Stream and the Eastwyke Ditch, to also rise. These water courses spill over into their floodplains. The flood waters from the

Hinksey Stream flowing south, to the west of the railway line, are impeded by manmade ground and road embankments and restricted by the conduits through these; this contributes to the substantial rise in the Hinksey Stream. Although the flow of flood waters from the Hinksey Stream to the east is impeded initially by the built-up urban ground, flood waters eventually reach an elevation where they can break through at low points and through storm drains that normally drain west to the Hinksey Stream. This water makes its way east along some of the residential roads perpendicular to the Abingdon Road, then flow south on the road and accumulate in the low-lying area at the junction of the road with Weirs Lane. The Eastwyke Ditch forms another route for water flowing east, discharging into flooded ground to the west of the River Thames. The water from the Eastwyke Ditch additionally finds a route to the south through the Hinksey Lakes which in the past, prior to the introduction by the EA of flood barriers, could spill and flow east along residential streets.

The River Thames, above Iffley Lock, and the Weirs Mill Stream, upstream of the weirs, overbank to the west. They initially flood ground immediately in their vicinity. In time, as levels increase, water here starts to flow further west across the intervening ground, primarily the Cowmead Allotment, to the Abingdon Road where, like the water from the Hinksey Stream, it flows south towards the lowest point of the road close to the junction with Weirs Lane. The water also flows into the Cold Harbour area north of Weirs Lane although rarely into the houses. As flood waters deepen on the Abingdon Road they spread northwards up the road and partially into the residential roads perpendicular to it.

The Weirs Mill Stream downstream of the weirs has limited impact on property during floods. It flows east across the Iffley Meadows towards the River Thames downstream of Iffley Lock but also rises into the gardens that border it in Cold Harbour.

Groundwater flooding occurs as the sole form of above-ground flooding in some areas, in particular in gardens in Cold Harbour and New Hinksey, and in basements in Grandpont. These areas are protected from fluvial flooding due to built-up urban land. Where areas are not protected by built-up land (i.e. floodplain meadows, agricultural land, sports grounds and allotments), groundwater flooding occurs initially prior to subsequent fluvial flooding as river levels rise and overflow their banks. The most impactful form of groundwater flooding is below-ground on the sewerage network. This causes the poor functioning of toilets and wastewater networks. It is estimated by the author from community feedback that this affects hundreds of properties in HPW.

Groundwater levels are strongly linked to river levels, as evidenced by the data already presented, and to be analysed in Chapter 3. The occurrence and timing of groundwater flooding is determined by the relative elevations of river and ground, and the proximity of the rivers. Areas of Cold Harbour, which have elevations close to those of the adjacent River Thames and Weirs Mill Stream, are the first urban areas to see groundwater flooding. The majority of groundwater flooding that occurs in New Hinksey occurs later. There are limited areas in Grandpont that see groundwater flooding, these being primarily as a consequence of the conversion of basements. It is possible that the initial flooding that occurs at the low point of the Abingdon Road is caused by groundwater or by subsurface flow through the drainage network, prior to the fluvial flooding described above.

If there are no subsequent rainfall events, rivers can return to non-flood levels within 1-2 weeks. As river levels recess, some fluvial flood waters are trapped in low-lying areas of the floodplain. The saturated ground and the relatively low permeability of the alluvium can cause these floods to persist in some locations for weeks, although this is based on anecdotal information and not monitoring data. Groundwater levels recess at a slightly slower rate than river levels. The length of groundwater-only flooding is dependent on location but again is in the order of 1-2 weeks.

Figure 2.14 is a schematic that shows the thicknesses of the geological layers and the manmade ground in a representative west to east cross-section through the Hinksey Park Ward. It shows flood water levels at the

time of the peak fluvial flood. The flooding between houses on Wytham Street and the Abingdon Road is due to a rise in groundwater levels driven by the pressure of fluvial flood waters to the west and east, with an expected minor contribution from lateral flow of water through the made ground; note, at the time represented in Figure 2.14, groundwater levels have not reached their peak.

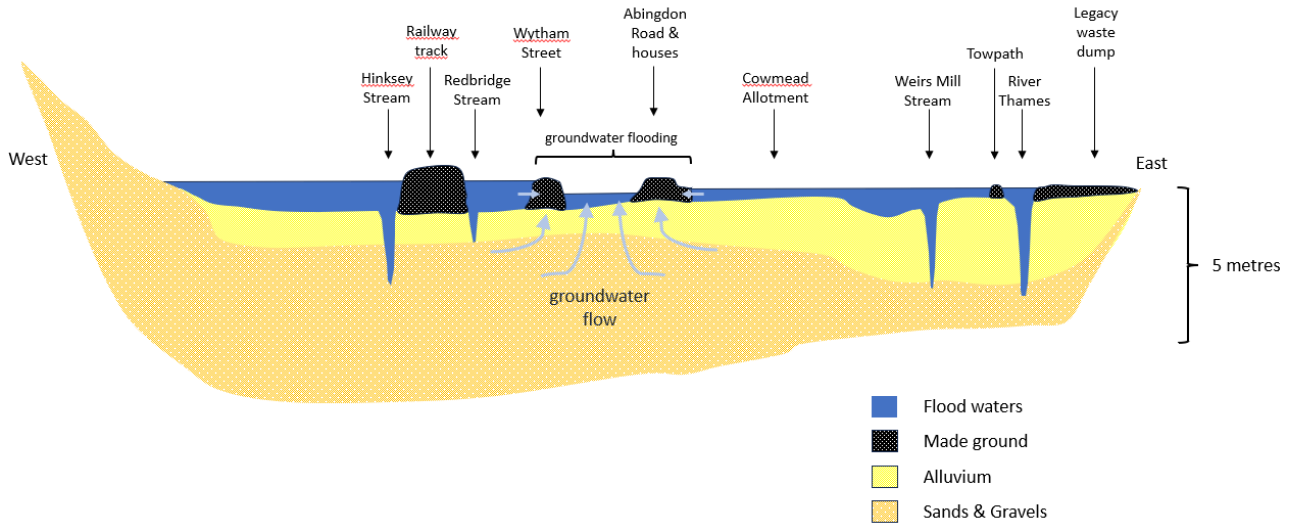


Figure 2-14 West-east cross-section schematic through HPW showing typical ground and building elevations, as well as geology and river and groundwater level. Line of section is shown in Figure 2.13

2.4.2 Further detail on mechanisms and sequencing

Here, more detail is provided on the mechanisms and sequencing of a typical flood event, referencing locations. This analysis uses a combination of monitored river and groundwater levels and topographic elevations as well as the observations of local residents. The areas included in the descriptions are demarcated in the accompanying figures (Figures 2.15-2.20). Figure 2.15 identifies all the areas. Note, the areas demarcated are those within which the flooding described occurs without it necessarily affecting the whole of that area:

- high river levels prior to a flood-inducing rainfall event (Figure 2.16):
    - areas of the Hinksey Stream floodplain to the west of the railway line have groundwater flooding
    - groundwater flooding in the area just west of the River Thames and Weirs Mill Stream upstream of the weirs, as well as areas of Iffley Meadows
- initial response to significantly high period of rainfall (Figure 2.17):
    - Dean's Ham has groundwater flooding and areas of the Hinksey Stream floodplain to the west of the railway line have further groundwater and fluvial flooding
    - area just west of the River Thames and Weirs Mill Stream upstream of the weirs, as well as areas of Iffley Meadows continue to wet up, including both groundwater and fluvial flooding
    - groundwater flooding in small areas of the Cowmead Allotment
    - groundwater flooding affects wastewater systems in Fox Crescent and can be seen in the gardens of houses in Chatham Road in Cold Harbour
- Indications of a more serious flood occurring (Figure 2.18)
    - Hinksey Stream floodplain fully covered, as is Dean's Ham. Groundwater flooding of Hinksey Park football pitches, and South Oxford Bowls Club flooded from backing up of the Redbridge Stream. Water into gardens in houses on the west side of Wytham Street
    - fields to the west of the Thames flooded, with further groundwater flooding of the Cowmead Allotment as well as potential for some water to flow through the allotment onto the

Abingdon Road. Flooding of the Abingdon Road/Weirs Lane junction begins – initially possibly groundwater flooding but then fluvial flooding. Iffley Meadows completely flooded
    - further groundwater flooding of gardens in the Cold Harbour area
    - gardens of some houses on Fox Crescent and Canning Crescent in Cold Harbour start to flood from the Weirs Mill Stream
    - flooding of inhabited basements of houses in Grandpont begins and gardens of houses in Western Road flooded by Hogacre Ditch, where not culverted
- towards the flood peak (Figure 2.19)
    - Hinksey Stream overspilling Wytham Street, flowing down Northampton Road and others
    - Eastwyke Ditch overspilling and flowing into the northern Hinksey Lake causing increase in rate of rise of the lake – EA lake barrier in place by this time. Flow from Eastwyke Ditch into the football pitches in Hinksey Park
    - gardens flooded by the River Thames/Weirs Mill Stream at the east end and north side of Chatham Road. Areas of groundwater flooding in other gardens in Cold Harbour getting greater
    - further flooding of fields to the west of the River Thames
    - water flowing through Cowmead Allotments from the River Thames on to Abingdon Road which is now likely to be closed
    - flooding on the Abingdon Road deepens with flood water extending north up the Abingdon Road and into roads perpendicular to it
    - further flooding of gardens of houses on Fox Crescent and Canning Crescent from the Weirs Mill Stream
    - some isolated groundwater flooding in gardens in New Hinksey
- flood at peak (Figure 2.20)
    - eastward flow of the Hinksey Stream through New Hinksey further increased. Water flows onto Bertie Place field and streets in the area of the southern end of Abingdon Road
    - northern Hinksey Lake spills over into the southern lake helping to increase flood levels at the South Oxford Bowls Club and in gardens on the west side of Wytham Street
    - water from the River Thames flows at a greater rate on to Abingdon Road through Cowmead Allotments. Water also flowing into the streets of Cold Harbour. Groundwater flooding seen in gardens across Cold Harbour
    - flooding on the Abingdon Road deepens with flood water extending further north up the Abingdon Road and roads perpendicular to it
    - many gardens and some properties flooded above ground floor level in New Hinksey
    - some gardens flooded in Grandpont

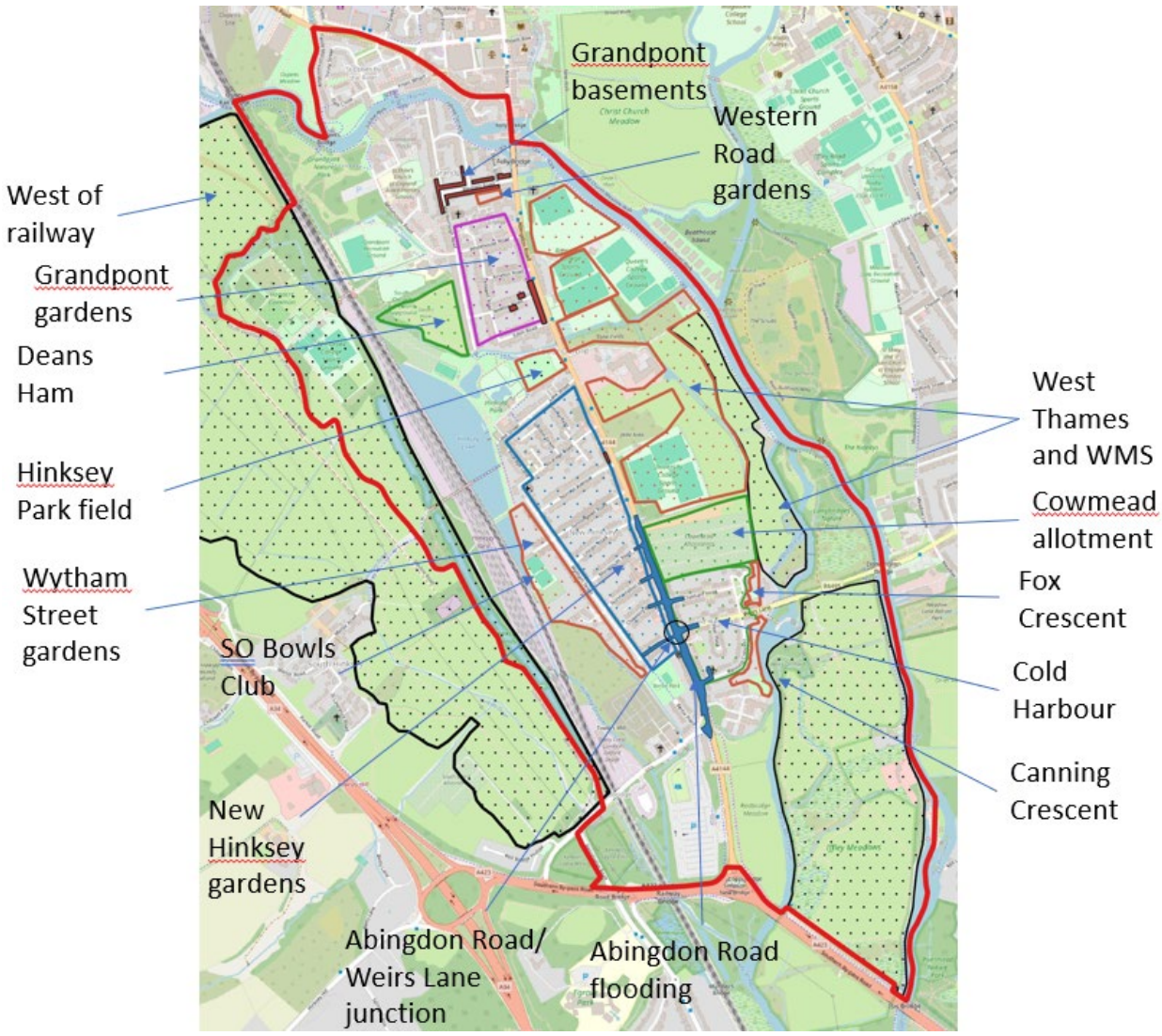


Figure 2-15 Areas referred to in description of mechanisms and sequencing of flooding in HPW

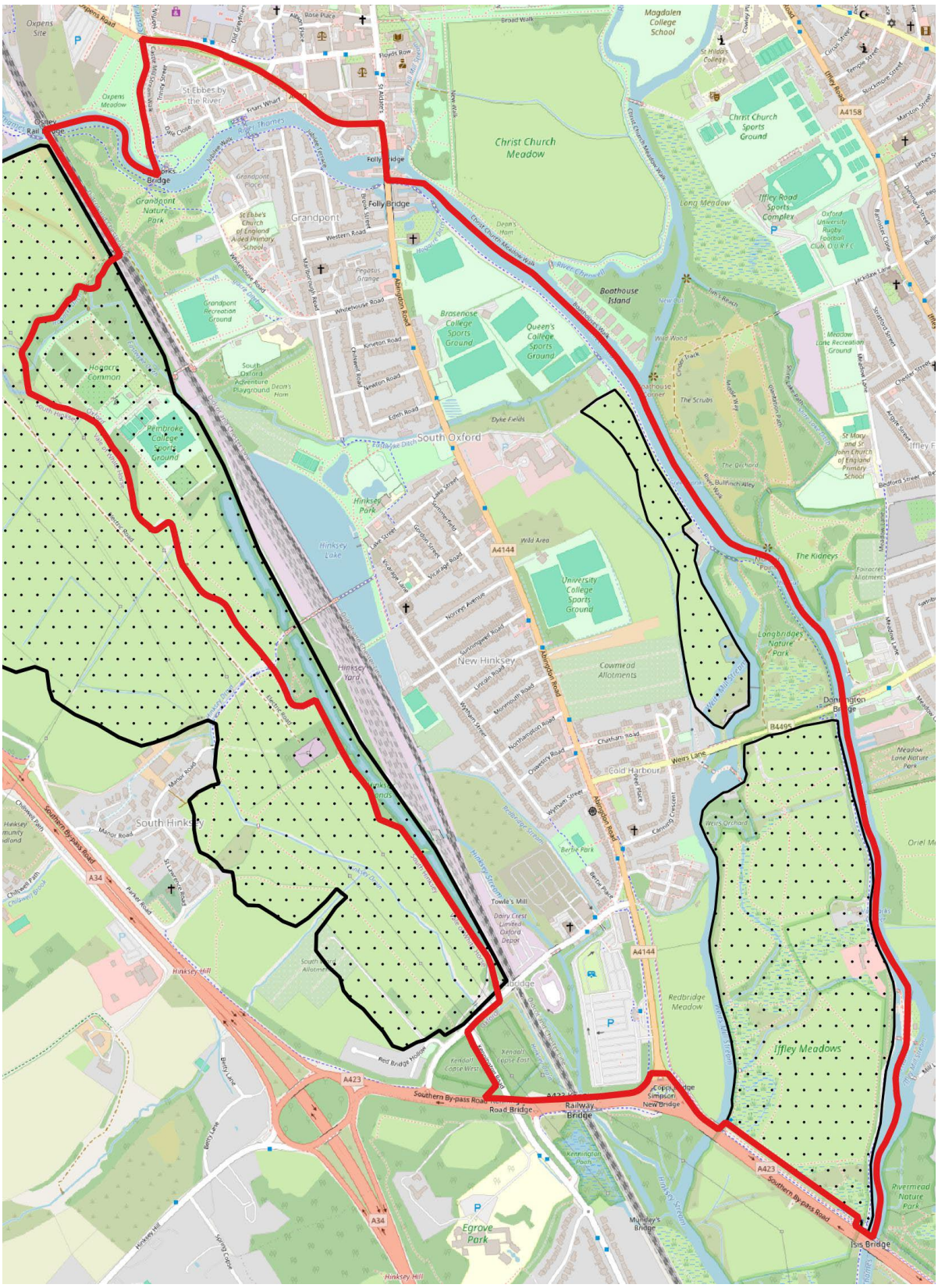


Figure 2-16 Areas with groundwater flooding when river levels are high, prior to a flood-inducing rainfall event (areas of black stippling)

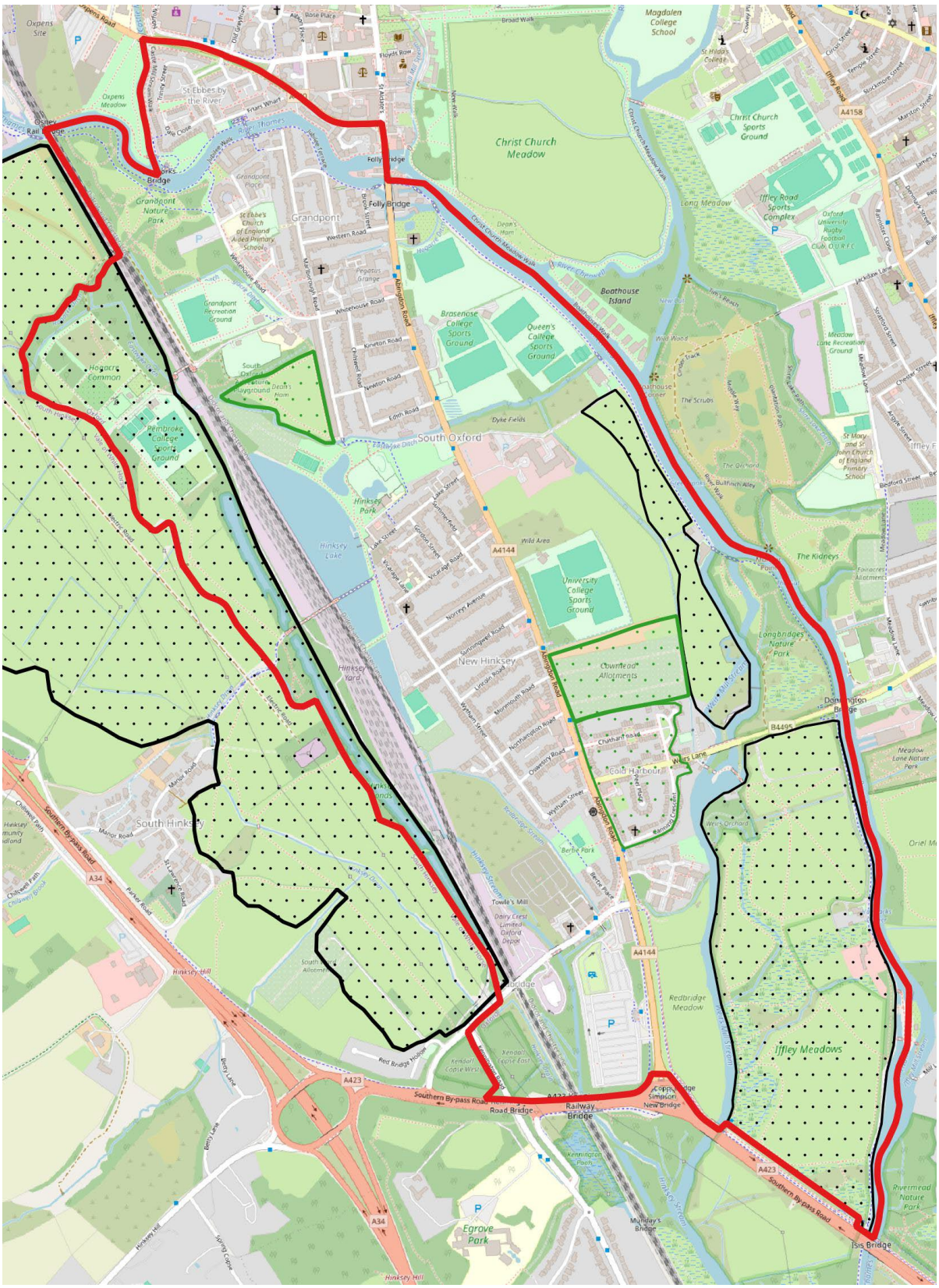


Figure 2-17 Flooding in the initial period following a significantly high period of rainfall (additional green stippling to Figure 2.16)

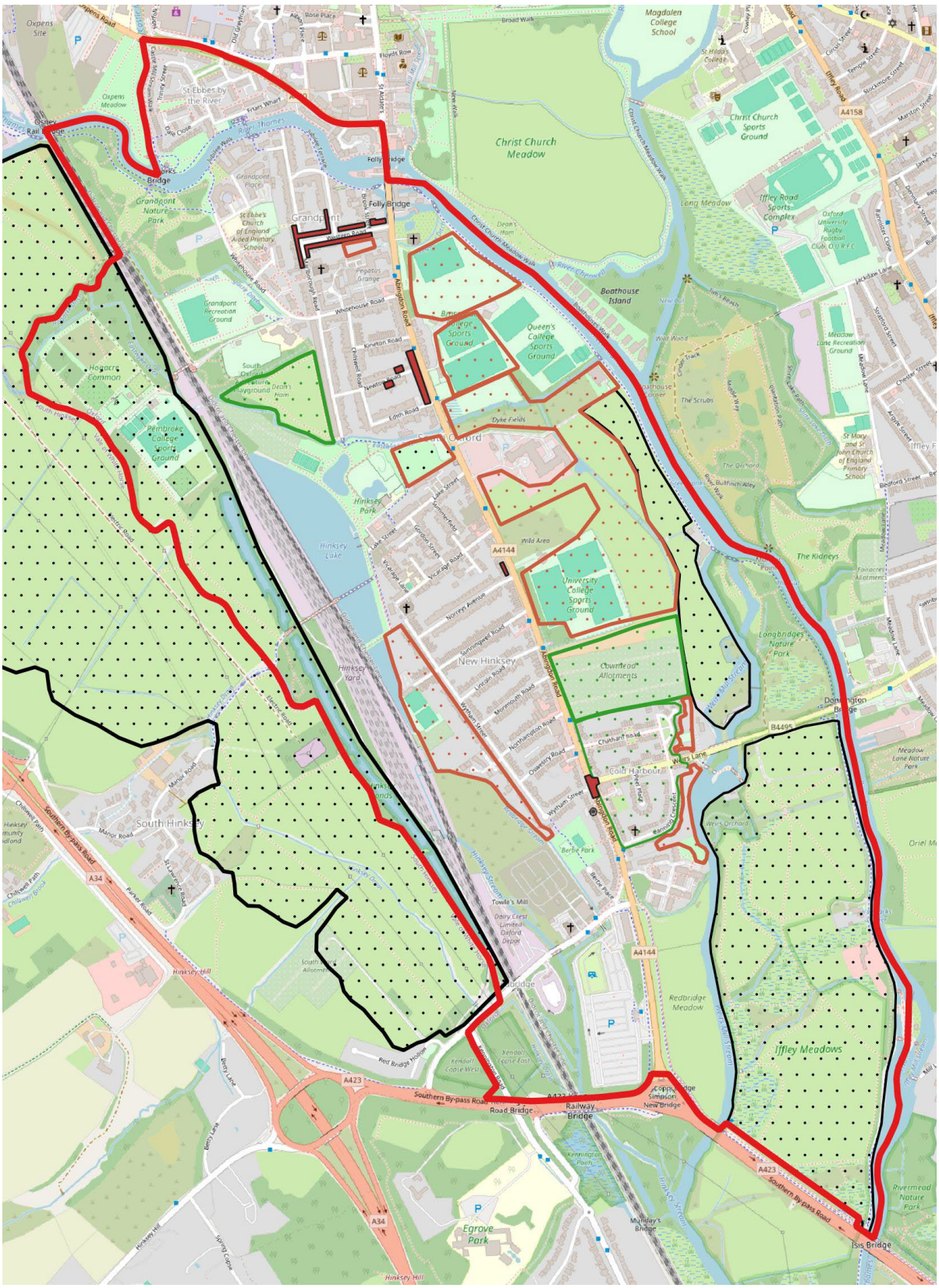


Figure 2-18 Areas indicating more serious flooding occurring (additional orange stippling to Figures 2.16 and 2.17, plus orange blocks identifying properties with basements)

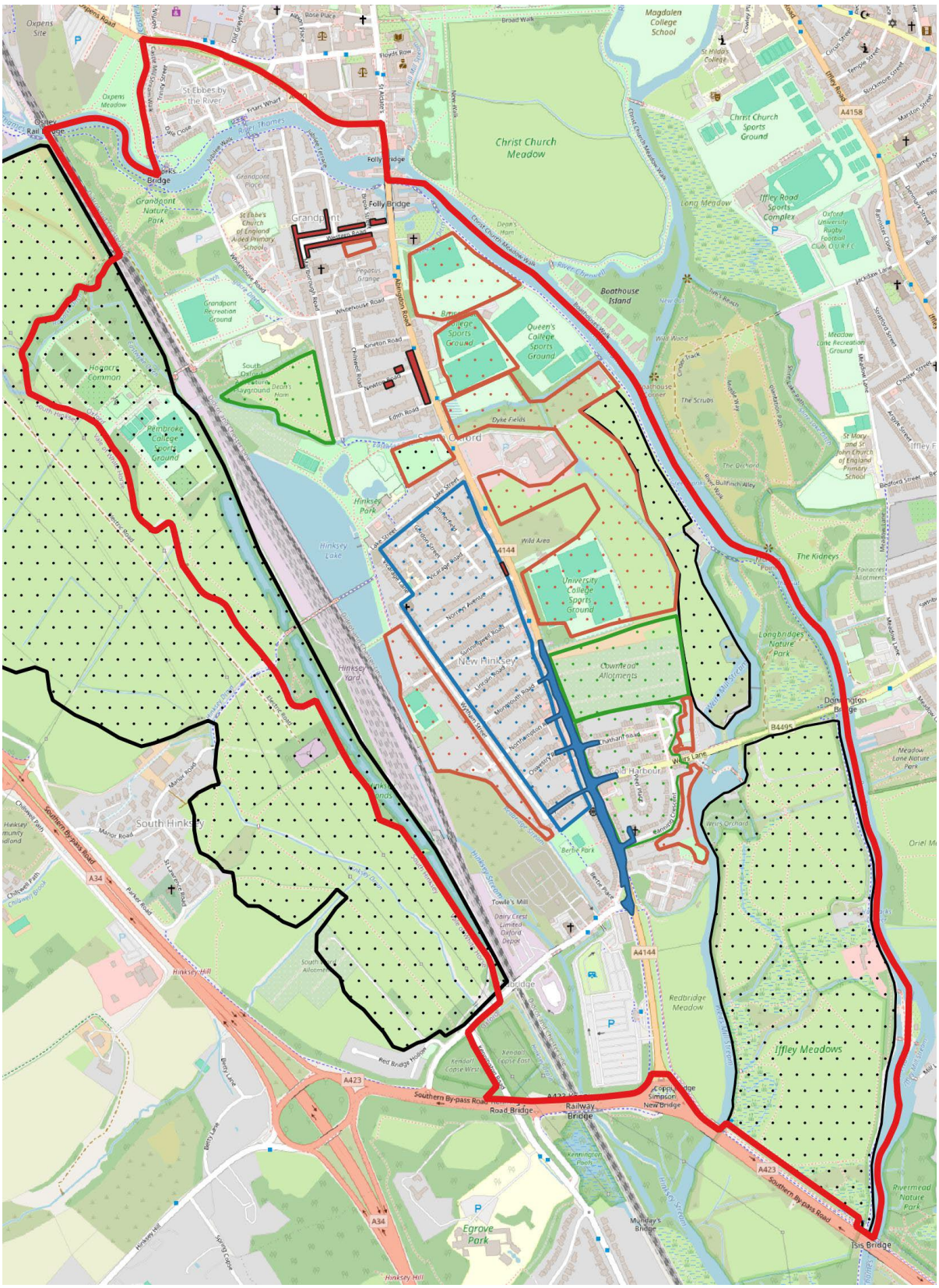


Figure 2-19 Flooding heading towards peak levels (additional blue stippling to Figures 2.16-2.18, plus blue areas identifying key flooded roads)

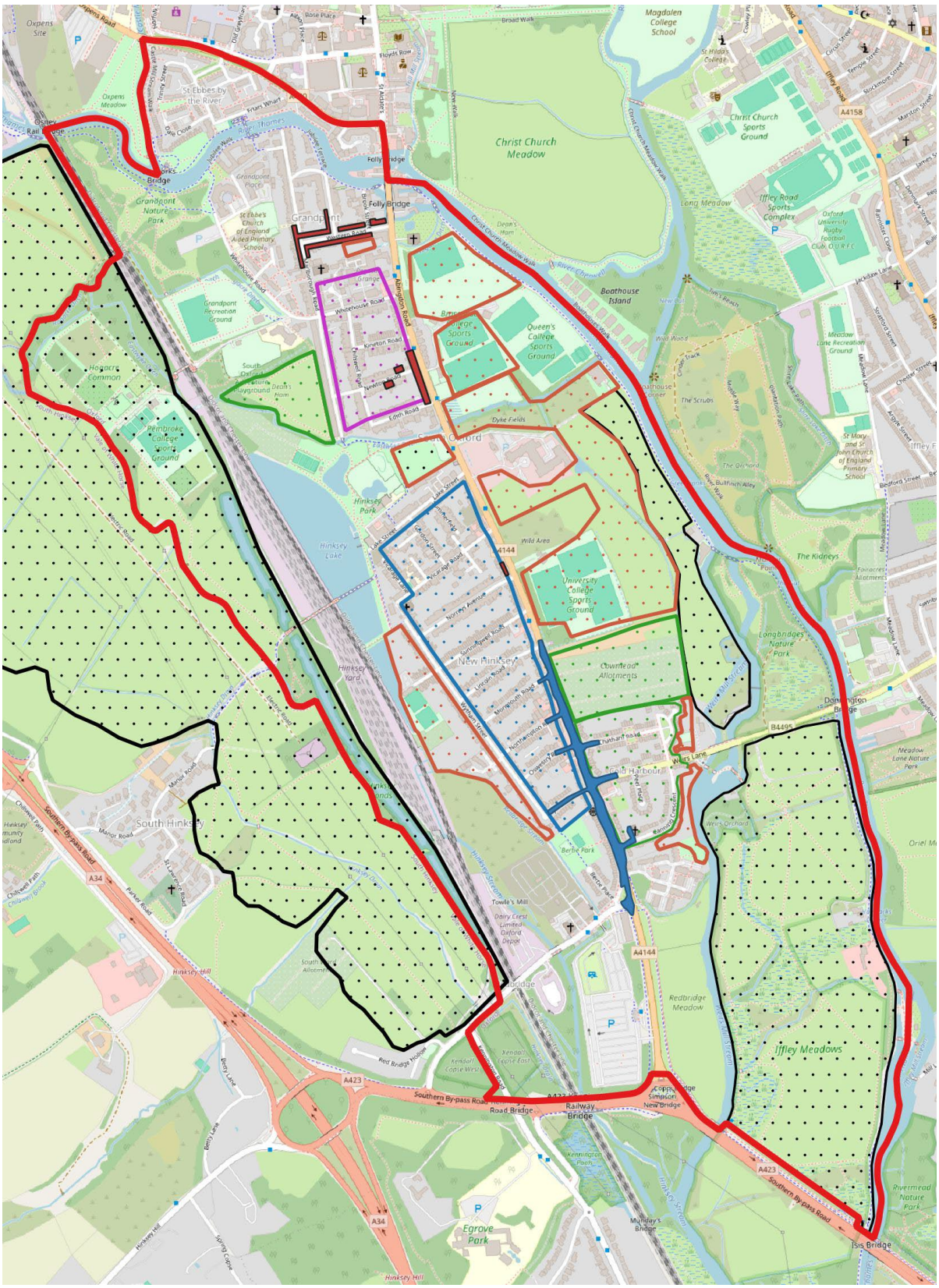


Figure 2-20 Flood waters at peak levels experienced in past two decades (additional purple stippling to Figures 2.16-2.19)

2.5 KNOWLEDGE GAPS

Improvements could be made to the conceptualisation of the flooding in HPW. The objectives of this would be to:

- improve the understanding of the nature, timing and extent of the flooding in the area and the resulting impacts;
- help with the design of potential flood protection measures;
- provide the basis to assess better how the area might be affected by floods outside of the range of the recent historical floods.

In meeting these objectives, work could be undertaken to address the following gaps in knowledge (note, this list is not currently prioritised). It is recognised that investigation undertaken by the EA in designing the OFAS, including model development, may have addressed some of the knowledge gaps listed.

1. Improve the understanding of flood mechanisms and sequencing. Gather more data on water levels during floods through a monitoring network that allows measurements to be undertaken at sites on rivers and streams that are closer to the areas of impact and at locations that would allow thresholds for breakthrough of fluvial flood waters to be established.
2. Increase the knowledge of the nature and impact of historical floods on the local community to help identify the need for improved protection measures. This could include the collation and analysis of insurance claim data.
3. Improve the understanding of how waters recess after flood events. Making more detailed observations of location and persistence of flood waters could be undertaken by a more systematic set of observations post-flood and through both consultation with local residents and a network of monitoring sites.
4. Improve the understanding of the response of the groundwater system to the rise in river levels to identify the spatial variation in risk to properties. Again, these data could be gathered involving local residents and using an improved groundwater level data monitoring network.
5. Improve the understanding of the role of the subsurface channels in routing water during floods, including sewers, storm drains, and associated with other utilities. This could involve mapping the location and elevations of these channels and how these relate to groundwater levels and geological horizons.
6. Explore the role of groundwater in the persistence of flood waters at the Abingdon Road/Weirs Lane junction. This would involve the monitoring of both the flood water and groundwater level at the location, in conjunction with the timing and amount of pumping undertaken by the Fire Service.
7. Assess how the area would be affected by floods outside of the range of recent historical floods. This would use modelled flood water levels for low probability events. Given that models have already been developed for the purpose of designing protection measures associated with the OFAS, an assessment is required as to whether the current modelling, including groundwater modelling, is fit-for-purpose and the uncertainties within acceptable. To improve uncertainties in groundwater modelling there might be a need to improve the data on the thicknesses and hydraulic properties of geological and manmade layers in the wider area.

3 POTENTIAL FOR FLOOD EARLY WARNING IN HPW

3.1 INTRODUCTION TO FLOOD EARLY WARNING

As highlighted in the introduction to this report, given the challenges with developing new groundwater monitoring infrastructure, PG is exploring the potential to use the existing EA river level monitoring network for early warning in areas prone to PSD groundwater flooding. Here we look specifically at the potential for

HPW. A stepwise approach is taken: firstly, further investigation is undertaken as to whether there is sufficient correlation between river levels and groundwater levels within HPW and what the lag is between the two; secondly, river level response during periods of flooding in HPW is characterised based on the major events that have occurred in the past two decades; and finally, there is examination of whether upstream river level thresholds can be identified that result in flooding in HPW and what lead in times these provide.

3.2 CORRELATION BETWEEN RIVER AND GROUNDWATER LEVELS DURING FLOODS

In assessing the relationship between river and groundwater levels, paired time series were required. As highlighted in Chapter 2, past investigations relating to flood, drought, pollution and ecology have resulted in a large number of monitoring boreholes and river stilling wells being installed within the floodplain of the River Thames and its tributaries in the Oxford area. Paired river and groundwater time series datasets were used from across the floodplain, not solely within HPW, to maximise results. Data collected from the monitoring network includes a mix of manual dips and automated measurements obtained using water level sensors. The sensor data were commonly obtained at an interval of 15 to 60 minutes. In addition, there are the datasets from the EA river stations monitoring river levels at an interval of 15 minutes.

The manually dipped water level data are not frequent or regular enough to allow an adequate analysis of the relationship between groundwater and river water level. The analysis is therefore only possible where sensor data are available. These time series are of variable lengths; in some cases the sensors were only in place for periods of a couple of years. In selecting groundwater level time series to include in the analysis, a criterion was used of a minimum of eight years of data, with only limited gaps in data within this time.

When setting up the monitoring network, it was necessary to complete some of the boreholes at or just below ground level, as they were located in environmentally sensitive sites (note, completing is the process of: sealing around the top of the borehole so that water from the surface cannot flow vertically down into the ground through the disturbed loose material surrounding the borehole; and the installation of a removable cap to the borehole.) Although completed with water-tight caps, it is recognised that these may have been compromised at some point during the period that the boreholes were being monitored. Where these boreholes are prone to inundation by fluvial floods there is concern that the data may have been compromised, therefore data from these sites were not included in the analysis.

Table 3.1 lists the 10 pairs of boreholes and river stations that were available based on the above criteria. The river monitoring site that provided levels most reflective of those local to the groundwater in the borehole are also listed in the table; all boreholes and river stations are shown in Figure 2.2. The relevant river and the perpendicular distance of the borehole from this are include in Table 3.1. It is acknowledged that given the extensive network of rivers, streams and ditches in the Oxford floodplain that there may be two or more water courses in the vicinity of a borehole. Only one pair of groundwater and river level datasets were used for each borehole due to limited time but additional combinations could be considered as part of the further analysis proposed in Chapter 4. The groundwater and river level datasets that were used were subsampled to hourly to ensure consistency across the time series. Table 3.1 includes the period of the data and the number of data points available.

The relationship between river and groundwater levels is assessed by calculating the Pearson correlation coefficient between the pairs of time series. The results are presented in Table 3.2 and illustrated in Figures 3.1 and 3.2). Correlations are calculated separately for: the full dataset; the highest 5% of groundwater levels; and the highest 1% of groundwater levels.

Table 3-1 Borehole/river station pairings used to analyse relationship between river levels and groundwater levels in the Oxford floodplain, with information on the overlapping time series

Borehole	Easting	Northing	River station	Easting	Northing	River	River distance (m)	First record	Last record	no. data points
PX5	448112	210490	KingsHead	447903	210265	Wolvercote Millstream	70	29/06/2005	08/11/2016	88703
WR3	446340	210356	TPX27	-	-	-	373	02/09/2005	26/12/2013	62866
PX27	446945	210170	TPX27	446946	210167	Thames	3	27/10/2004	06/04/2015	69473
HFM1	448021	208204	DHFM1	448026	208206	Seacourt Stream	11	19/12/2005	06/04/2015	81066
OS3	449656	206309	NewBotley	-	-	-	59	19/12/2005	15/06/2014	79037
OS1	449831	205723	NewBotley	449708	206242	Bulstake Stream	15	19/12/2005	27/06/2014	73514
SH3	450092	205112	DSH3	-	-	-	4	19/12/2005	27/06/2014	70751
NH3	451236	204918	DSH3	-	-	-	335	19/12/2005	27/06/2014	73846
NH1	451700	204401	DSH3	450095	205114	Hinksey Stream	350	19/12/2005	27/06/2014	56739
SH1	451342	203832	ColdHarbour	451791	203852	Hinksey Stream	165	07/04/2005	27/06/2014	79847

Table 3-2 Pearson Correlation Coefficients for river and groundwater level pairings and the lag of groundwater behind river level for the highest 5% and 1% of groundwater levels for each pair

Borehole	River station	River distance (m)	All data		Highest 5% of gw levels			Highest 1% of gw levels		
			#data	Correl.	#data	Correl.	Lag (hrs)	#data	Correl.	Lag (hrs)
PX5	KingsHead	70	88703	0.66	4999	0.93	6	1089	0.70	4
WR3	TPX27	373	62866	0.71	2281	0.89	3	410	0.92	2
PX27	TPX27	3	69473	0.92	3709	0.97	1	781	0.96	0
HFM1	DHFM1	11	81066	0.97	4057	0.98	1	837	0.94	1
OS3	NewBotley	59	79037	0.98	4759	0.96	8	988	0.95	3
OS1	NewBotley	15	73514	0.99	4787	0.98	4	988	0.95	3
SH3	DSH3	4	70751	0.98	3674	0.99	0	761	0.98	0
NH3	DSH3	335	73846	0.88	3726	0.96	10	761	0.97	7
NH1	DSH3	350	56739	0.87	3515	0.93	20	761	0.79	20
SH1	ColdHarbour	165	79847	0.65	4927	0.69	13	953	0.81	6

The correlation coefficients are classified as strong across all the pairings for all the data and the two subsets. There is no consistent trend in the coefficients across the sets of data. There is a weak overall inverse linear relationship between correlation coefficient and distance from the borehole to the nearest river (Figure 3.1) but with no obvious physical explanation of the anomalies. These results suggest that it would be reasonable to assume across the Oxford floodplain that river levels are a good indicator of the fluctuation of groundwater levels.

Both the highest 5% and 1% of groundwater levels lag the river levels within the range of 0 to 20 hours. In almost all cases the lag time is reduced for the highest 1% dataset. This may be because rivers are out-of-bank and closer to monitoring boreholes. It may also be that bed sediments decrease the hydraulic connection between river and PSD and that at higher river levels these sediments are absent or thinner.

The pair of river and groundwater level time series that is of most relevance to groundwater flooding in HPW is NH1 and DSH3. NH1 is located within a garden in New Hinksey which has been impacted by groundwater flooding in all 13 of the major events since 1998. Unlike sites of other boreholes used in the analysis, there is an elevated urban area surrounding NH1 that keeps fluvial flood waters some distance from the borehole.

This may be the reason why for the highest 1% of groundwater levels the lag is noticeably greater and the correlation lower than for other pairings.

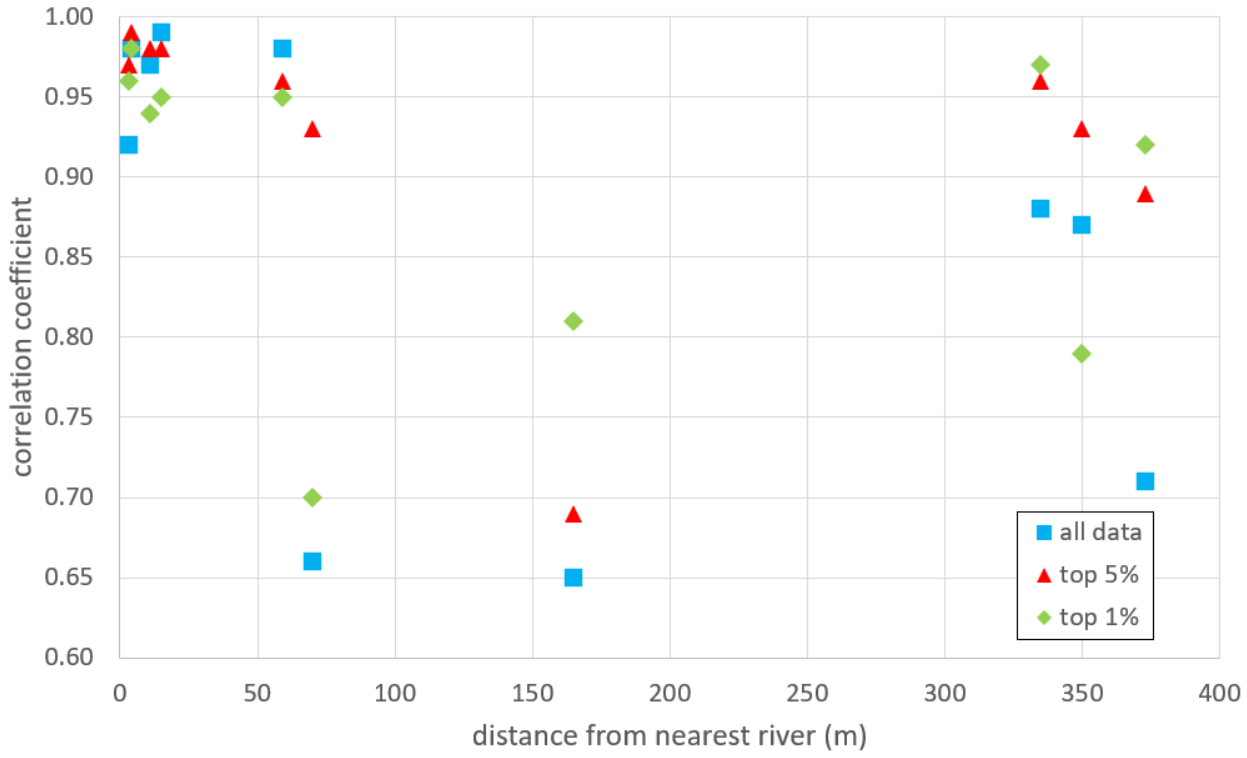


Figure 3-1 Correlation coefficient for pairs of river and groundwater time series against distances of the boreholes from the nearest river

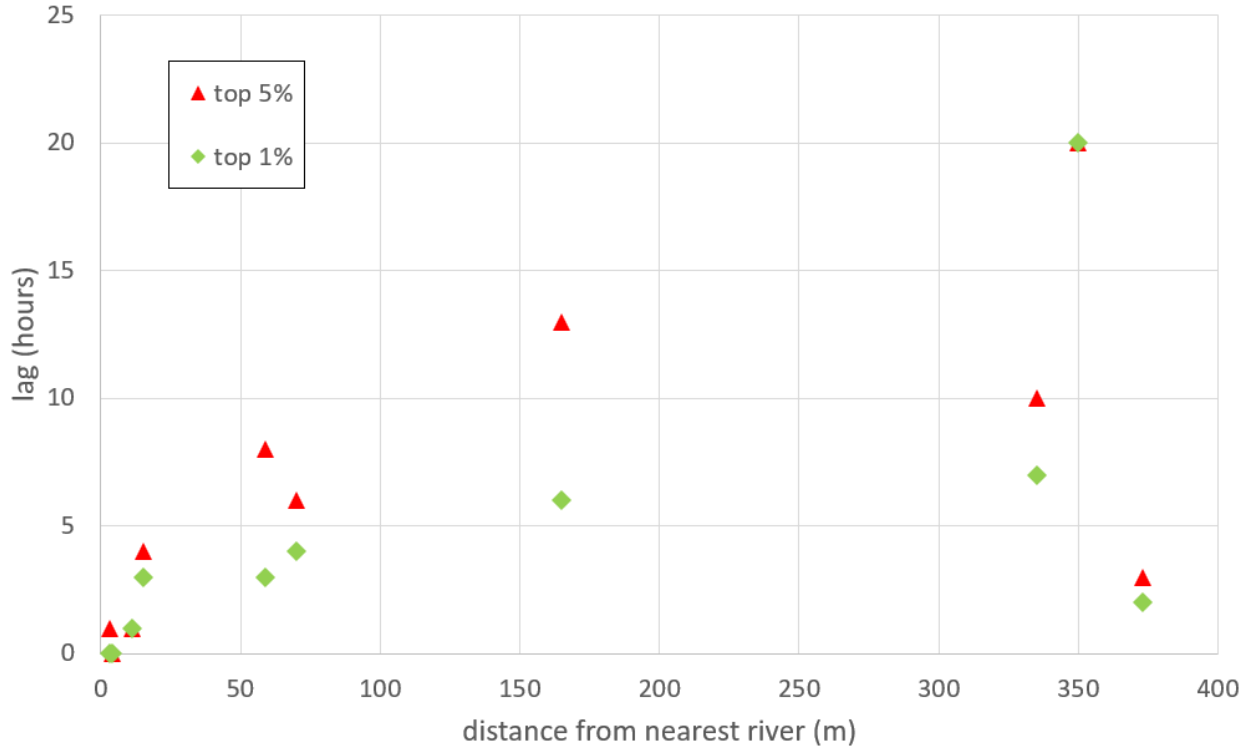


Figure 3-2 Lag of groundwater levels behind river levels for paired time series against distances of the boreholes from the nearest river

3.3 FLOOD CHARACTERISTICS

A summary of the broad flood mechanisms within HPW was described in the Section 2.4. As already shown, flooding in HPW is complex, with flood waters coming from Hinksey Stream in the west, the River Thames and the Weirs Mill Stream in the east, and upwards as groundwater from the gravels beneath. The complexity in how flooding happens is compounded by the number of rivers that join to flow past HPW: the River Thames itself that has a large catchment upstream of Oxford including the Cotswold Hills; the River Evenlode joins the Thames from the north just above Oxford; and the River Cherwell joins the Thames from the east downstream of the city's historic centre. The catchments of these rivers where they enter Oxford (Thames), or join the Thames upstream of or within Oxford (Evenlode, Cherwell), have a wide range in size (see Figure 2.2): Thames at Eynsham, 1627 km^2 (referred to in the analysis below as the Upper Thames); Evenlode at Cassington, 427 km^2; Cherwell at the Oxford Botanical Gardens, 907 km^2.

Given the spread of regions over which the catchments are located, rainfall within can be significantly different during a single potentially flood-inducing storm event. The topography, geology and the size and shape of the catchments also affect the timing of the flood peaks reaching the Oxford floodplain.

In developing flood early warning for HPW it is first helpful to examine the contributions of each of these rivers to flood events that have occurred in the past. In the Section 2.3, 13 major flood events were identified as having occurred since 1998 in HPW. Here we analyse all but the first two of the floods, in 1998 and 2000, as key river monitoring stations were not operating at that time. In the analysis we use the following EA river stations (Figure 2.2b; note, where the stations are located at locks on the River Thames, the downstream level is included in the analysis as this is more representative of the natural fluctuation of the river):

- River Thames - Eynsham Lock (downstream): this reflects the levels of the Thames flowing into the Oxford floodplain;
- River Thames – Northmoor Lock (downstream): there is some influence on the downstream level of Eynsham Lock due to the input of the River Evenlode, so Northmoor is used instead although it is not the last station on the Thames as it enters the Oxford floodplain;
- River Evenlode – Cassington B Weir: the last river station on the Evenlode before its confluence with the River Thames as it enters the Oxford floodplain;
- River Thames – Kings Lock (downstream): included to help assess the progress of the flood wave through the Oxford floodplain;
- River Cherwell – Botanical Gardens: the last river station on the Cherwell before its confluence with the Thames, just below the historic city centre of Oxford;
- River Thames – Iffley Lock (upstream): river levels upstream of the lock control flooding that affects the upgradient areas of Cold Harbour and the Abingdon Road;
- River Thames – Iffley Lock (downstream): these levels are more reflective of the natural fluctuation of the river but also flood levels in the downgradient areas of Cold Harbour;
- Seacourt Stream – Minns Estate: this station is just upstream of HPW (note, the Seacourt Stream changes its name to the Hinksey Stream as it passes North Hinksey village);
- Hinksey Stream – Cold Harbour: this station is at the downstream end of HPW and can be considered a proxy for flood conditions within the Ward. Although it is named Cold Harbour it is not adjacent to the area of HPW of that name, that is the Weirs Mill Stream.

The surface flow into the Seacourt Stream at its uppermost point occurs from the River Thames at a fixed head weir in the short reach between Eynsham Lock and Kings Lock; the River Evenlode joins the Thames along this reach, upstream of the weir. The River Evenlode appears to have a marked influence on the amount of water that flows from the Thames over the weir into the Seacourt Stream, which will be discussed below.

In addition to river levels, rainfall amounts at a series of gauges throughout the three main river catchments were reviewed (Figure 2.2a): Shorncote in the upstream area and Worsham in the downstream area of the

Upper Thames catchment; Chipping Norton in the River Evenlode catchment; Grimsbury in the upstream area and Bicester in the downstream area of the River Cherwell catchment. These are included, along with the flood hydrographs, in a series of figures, one for each event. To ease the comparison of events, all rainfall graphs use the same y-range of daily rainfall amounts and all hydrographs use the same y-range of water levels relative to local datum (note, Botanical Gardens uses the secondary y axis of the hydrograph plots). All rainfall graphs and all hydrographs use the same number of days, respectively, on the x axis, again, apart from Figure 3.8 for the Winter of 2013/14. The dates in the headings below are the approximate peak dates of river levels in the vicinity of HPW during the floods.

5 January 2003 (Figure 3.3)

This flood occurred as a result of a series of relatively small rainfall events (maximum 23mm), the majority of which affected the Upper Thames catchment over a period of 5 days (28 Dec 2002 - 1 Jan 2003). However, the River Thames levels were relatively high at the start of the event. The river levels in the Thames rose slowly, with the Evenlode having relatively little impact. The peak in the Hinksey Stream at Cold Harbour was just under a day after the peak in the Thames at Northmoor. The shape of the hydrograph was relatively symmetrical.

25 July 2007 (Figure 3.4)

This flood occurred as the result of a large storm event over 2-3 days (19-21 July) with total rainfall at the selected rain gauges of 60-120mm. The rainfall was particularly high in the Upper Thames and Evenlode catchments. Rivers reached record highs although the antecedent river conditions were low compared with those ahead of most autumn/winter floods. The River Evenlode level at Cassington peaked first and its influence can be seen at Eynsham Lock and stations downstream, including Minns Estate and Cold Harbour. The slower response of the Thames created a double peak, with the second, Upper Thames-related level being higher than the initial Evenlode-related peak in the Seacourt/Hinksey Stream. The first peak at Iffley Lock coincided with the peak in the River Cherwell at the Botanical Gardens.

19 January 2008 (Figure 3.5)

A series of rainfall events with a maximum of 32mm/d and an average of 13mm/d occurred over 6 days (10-15 Jan), focussed mainly within the Upper Thames catchment. The Evenlode had a small peak and limited influence on the shape of the downstream stations, which reflected the shape of the Northmoor and Eynsham hydrographs.

27 November 2012 (Figure 3.6)

A series of rainfall events with a maximum of 31mm/d and an average of 17mm/d occurred over 5 days (20-24 Nov), focussed mainly within the Upper Thames and Evenlode catchments. The overall shape of the hydrograph within the Oxford floodplain appears to be dominated by that of the flow from the Upper Thames although peaks in the river level at Cassington caused identifiable peaks in the Seacourt/Hinksey Stream. The peak at Iffley Lock would appear to be related to the input of the Cherwell although overall the Upper Thames dominated the shape of the hydrograph here.

28 December 2012 (Figure 3.7)

The river levels had not fully recessed following the Nov 2012 when a series of small amounts of rainfall from 19 Dec (average of 9mm/d) resulted in a further period of flooding during which all river levels maintained high stages.

Winter of 2013/14 (Figure 3.8)

The winter of 2013/14 saw record river levels across much of the Oxford floodplain and the upstream catchments. Rivers started mid-December at lower-than-average levels prior to a number of days of significant rainfall, with one notable event of ~35mm (23 Dec 2013), with a focus on the Upper Thames catchment. The Evenlode at Cassington peaked first on 25 December, approximately a day before the

Cherwell at the Botanical Gardens and 2 days before the Thames at Northmoor. However, the timing of the peaks in the Seacourt/Hinksey Streams was controlled by the Thames.

While river levels were still notably high, a period of ~11 days of small rainfall events across all the catchments upstream of Oxford (up to 8 Jan 2014) saw further flooding that peaked on 9 January in HPW (both Hinksey Stream at Cold Harbour and Thames at Iffley Lock), approximately a day after the peak in the Thames at Northmoor Lock.

Again, rivers had not returned to normal levels when a single event (of ~25mm on 6 Feb 2014), that impacted all catchments, caused further flooding. The peaks in the Thames at Northmoor and Iffley, and in the Seacourt at Minns Estate were within a couple of hours on 9 February, with Iffley peaking first, showing the influence of the Cherwell (Botanical Gardens data were absent for flood peak period).

It was not until mid-to-late March that rivers returned to normal levels for that time of the year, with a further peak in the interim but not one that caused flooding in HPW.

25 December 2020 (Figure 3.9)
A large rainfall event of ~42mm occurred on 23 December that affected primarily the catchments of the Upper Thames and Evenlode. Both of these rivers had above average levels already. The rainfall event caused an initial peak in the River Evenlode late on 24 December and then on 25 December in the Seacourt Stream at Minns Estate and very early on 26 December in the Hinksey Stream at Cold Harbour. The Cherwell also peaked early on 26 December just ahead of the Thames at Iffley Lock. It was not until 30 December that the Thames at Northmoor peaked. This was a few hours after second peaks in the Seacourt/Hinksey Stream and the Thames at Iffley, which were lower than the initial peaks due to the Evenlode and Cherwell.

3 February 2021 (Figure 3.10)
Coming on the back of the late December 2020 flood, a series of rainfall events in late January, including latterly a total of ~62mm over a period of 7 days (26 Jan – 2 Feb), caused further flooding. The period of high levels in the Seacourt/Hinksey Streams started before the peak level in the Thames was reached at Northmoor Lock, showing the influence of the Evenlode on the former. The period of high levels in the Cherwell occurred before the Hinksey Stream and meant the peak at Iffley Lock also was early than Northmoor.

5 January 2024 (Figure 3.11)
A rainfall event of ~20mm on 30 December 2023, followed by three similar days of rainfall over the following 5-day period caused a gradual increase in river levels. The River Cherwell peaked first (no data are available for the Evenlode at Cassington for this period), resulting in a peak soon after on 5 January in the Thames at Iffley. The first of two peaks in the Seacourt/Hinksey Streams later that day preceded the highest level in the River Thames at Northmoor by 2 days. This shows that the Evenlode had s significant influence on peak levels in the Seacourt/Hinksey Streams and in turn flood levels in HPW.

29 November 2024 (Figure 3.12)
Two significant rainfall days on 23 and 24 November resulted in flooding in HPW. The peak in the level in the River Evenlode at Cassington occurred on the afternoon of 25 December, with subsequent peaks at Minns Estate and Cold Harbour river stations on the evening of 26 and morning of 27 December, respectively. Again, data from the River Cherwell at the Botanical Gardens are missing but the Iffley Lock peaked early morning on 27 December. The Thames at Northmoor did not peak until 28 December. This resulted in a double peak in the Seacourt/Hinksey Streams although it was the second that was higher at Minns Estate and the first that was higher at Cold Harbour.

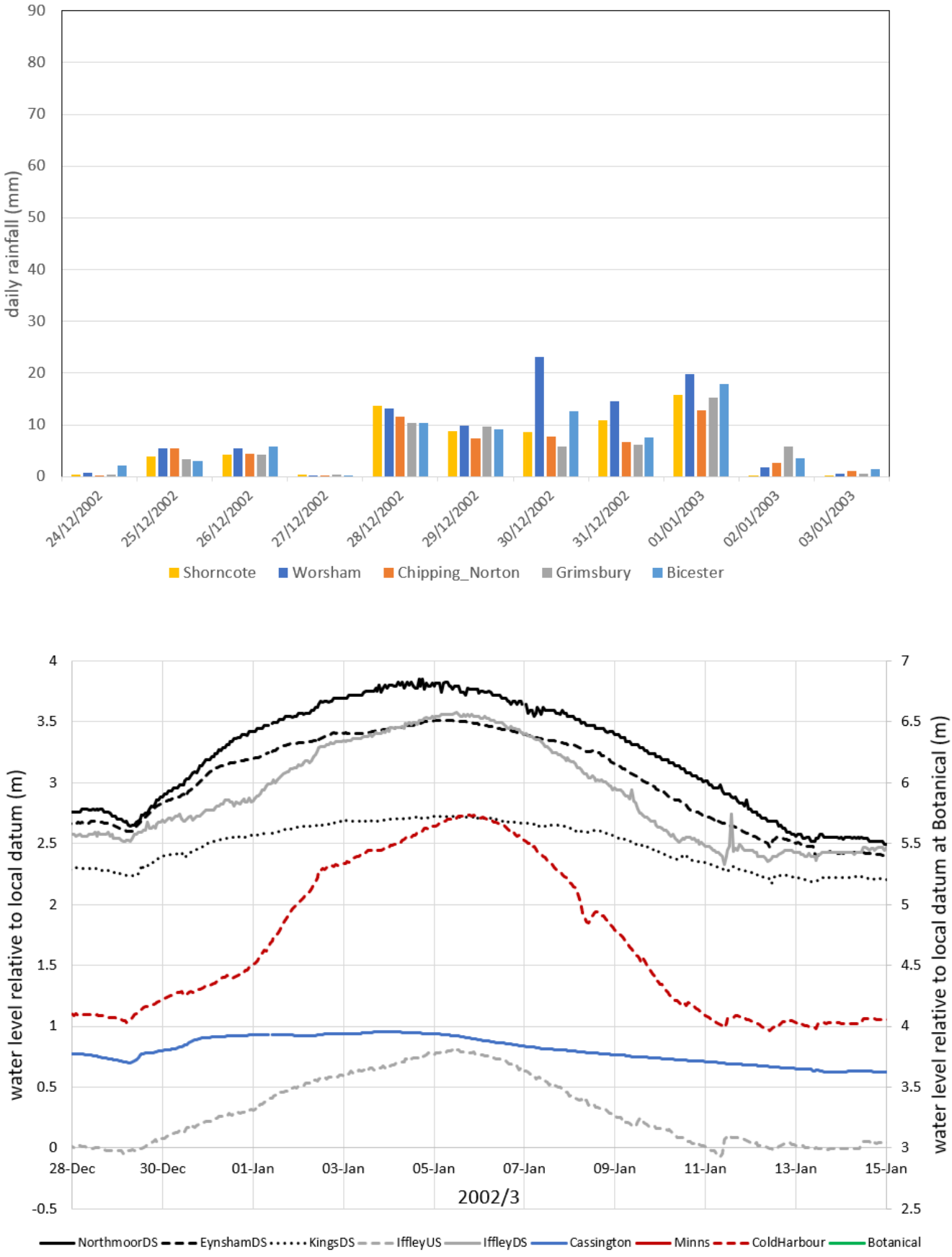


Figure 3-3 January 2003 flood: top - Rainfall at EA rain gauges within the Upper Thames, Evenlode and Cherwell catchments; bottom – hydrographs from river stations upstream of and within the Oxford floodplain

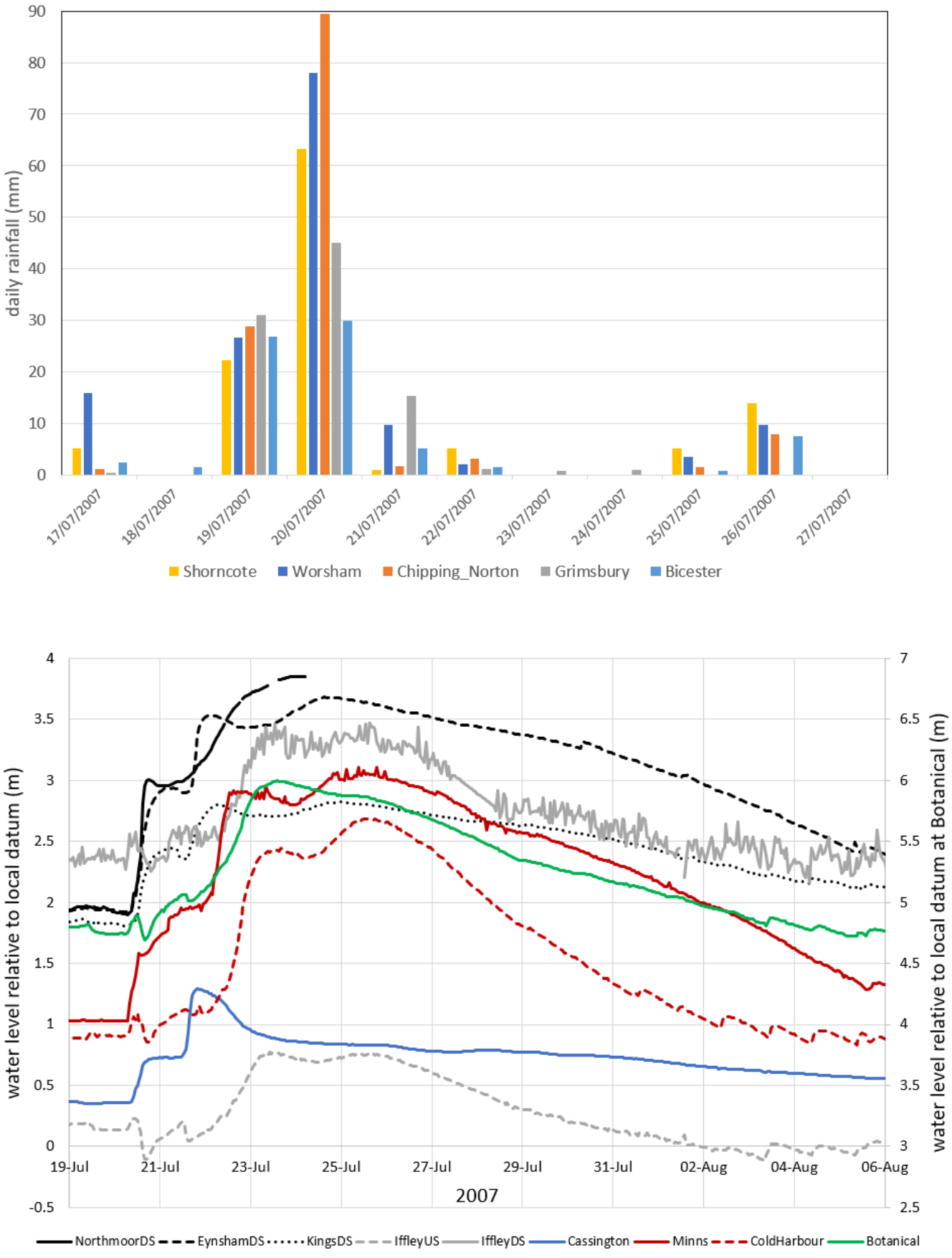


Figure 3-4 July 2007 flood: top - Rainfall at EA rain gauges within the Upper Thames, Evenlode and Cherwell catchments; bottom – hydrographs from river stations upstream of and within the Oxford floodplain

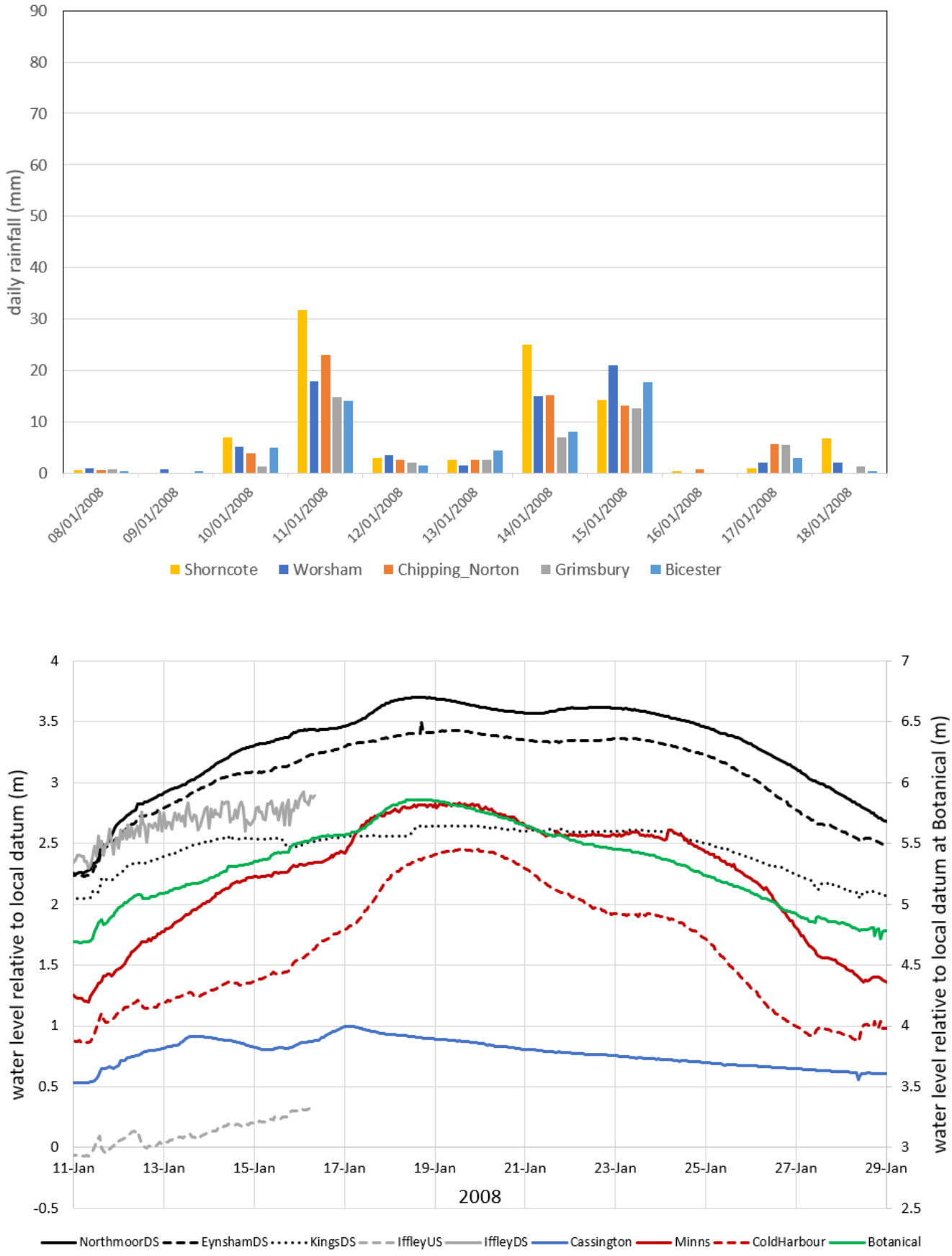


Figure 3-5 January 2008 flood: top - Rainfall at EA rain gauges within the Upper Thames, Evenlode and Cherwell catchments; bottom – hydrographs from river stations upstream of and within the Oxford floodplain

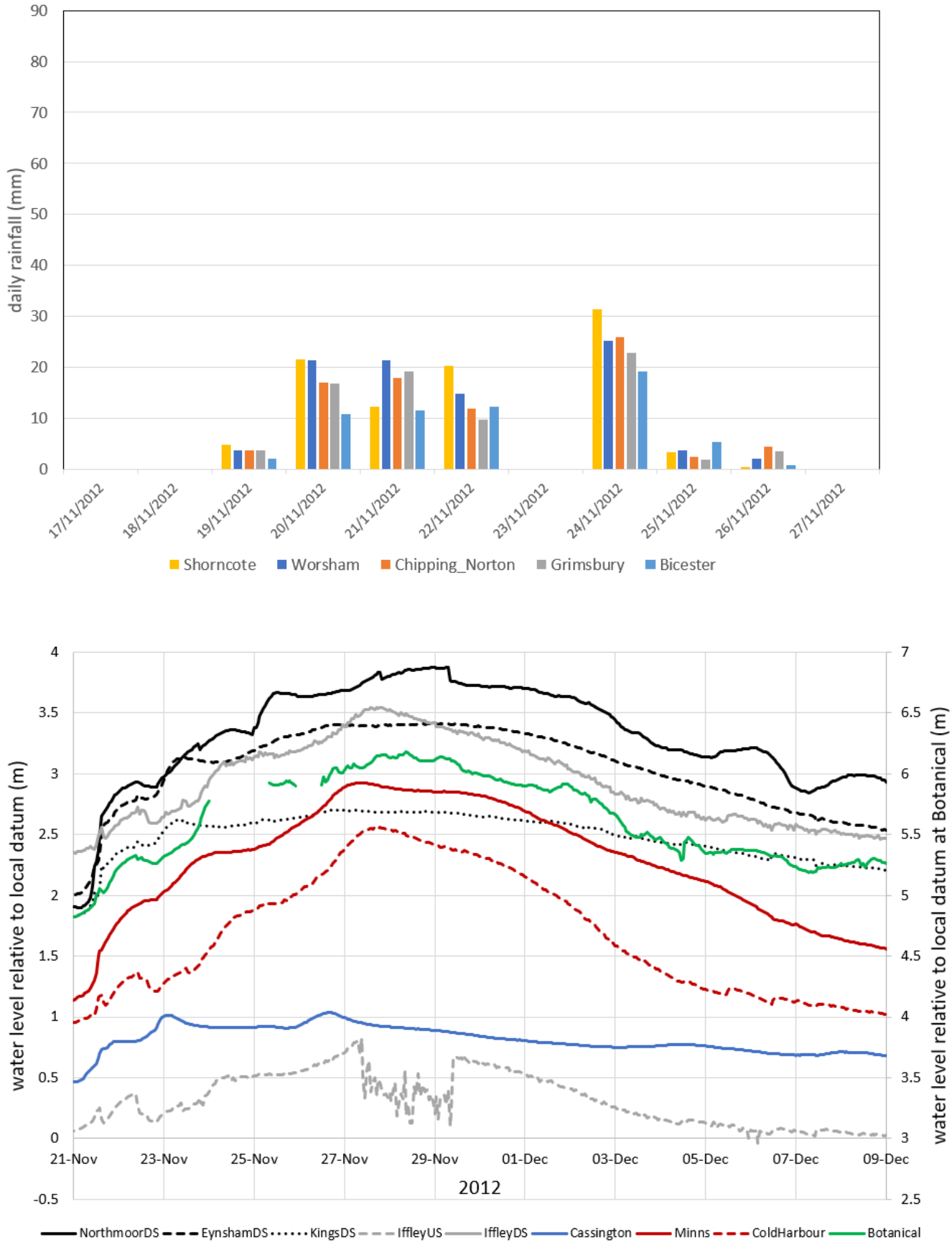


Figure 3-6 November 2012 flood: top - Rainfall at EA rain gauges within the Upper Thames, Evenlode and Cherwell catchments; bottom – hydrographs from river stations upstream of and within the Oxford floodplain

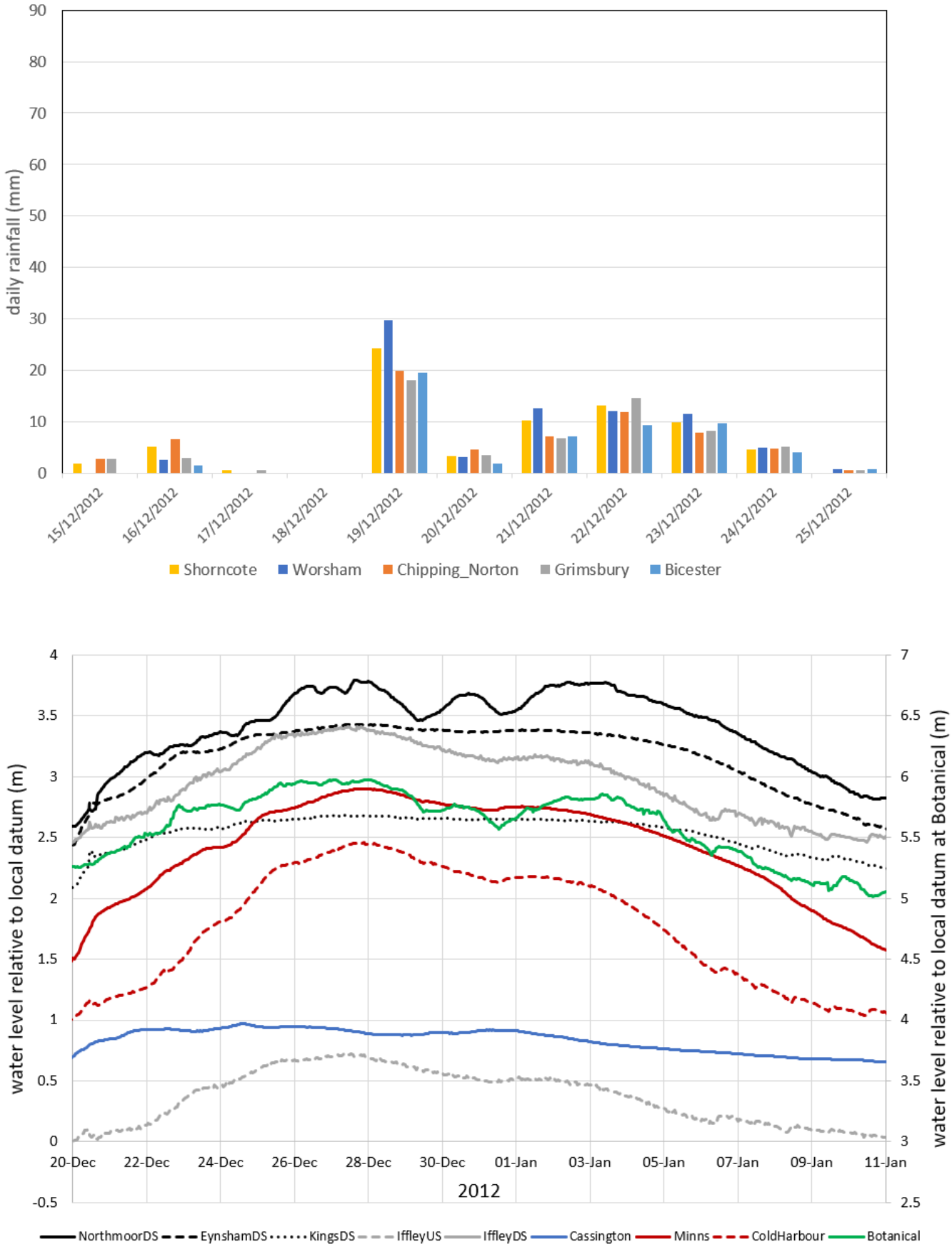


Figure 3-7 December 2012 flood: top - Rainfall at EA rain gauges within the Upper Thames, Evenlode and Cherwell catchments; bottom – hydrographs from river stations upstream of and within the Oxford floodplain

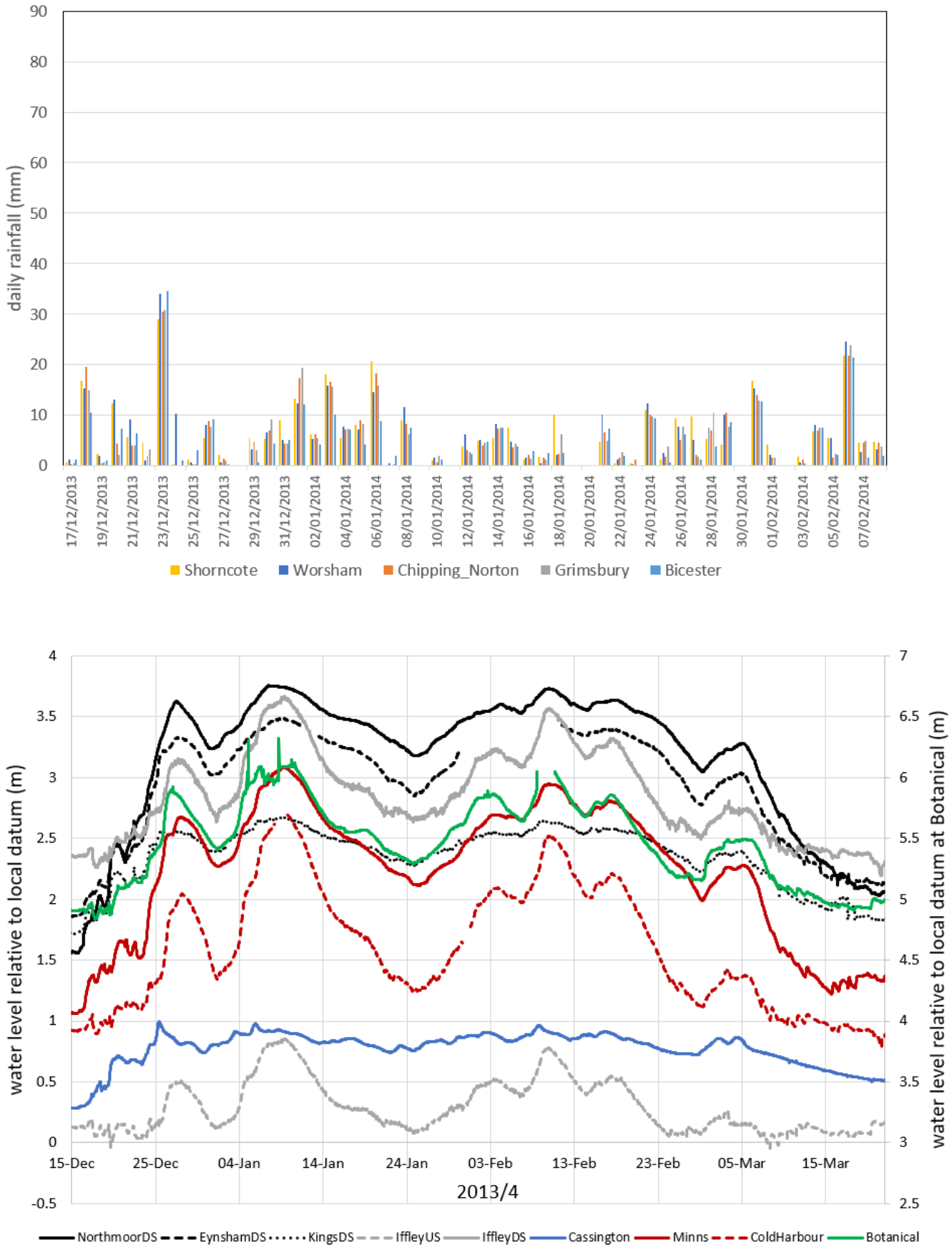


Figure 3-8 Winter of 2013/14 flood: top - Rainfall at EA rain gauges within the Upper Thames, Evenlode and Cherwell catchments; bottom – hydrographs from river stations upstream of and within the Oxford floodplain

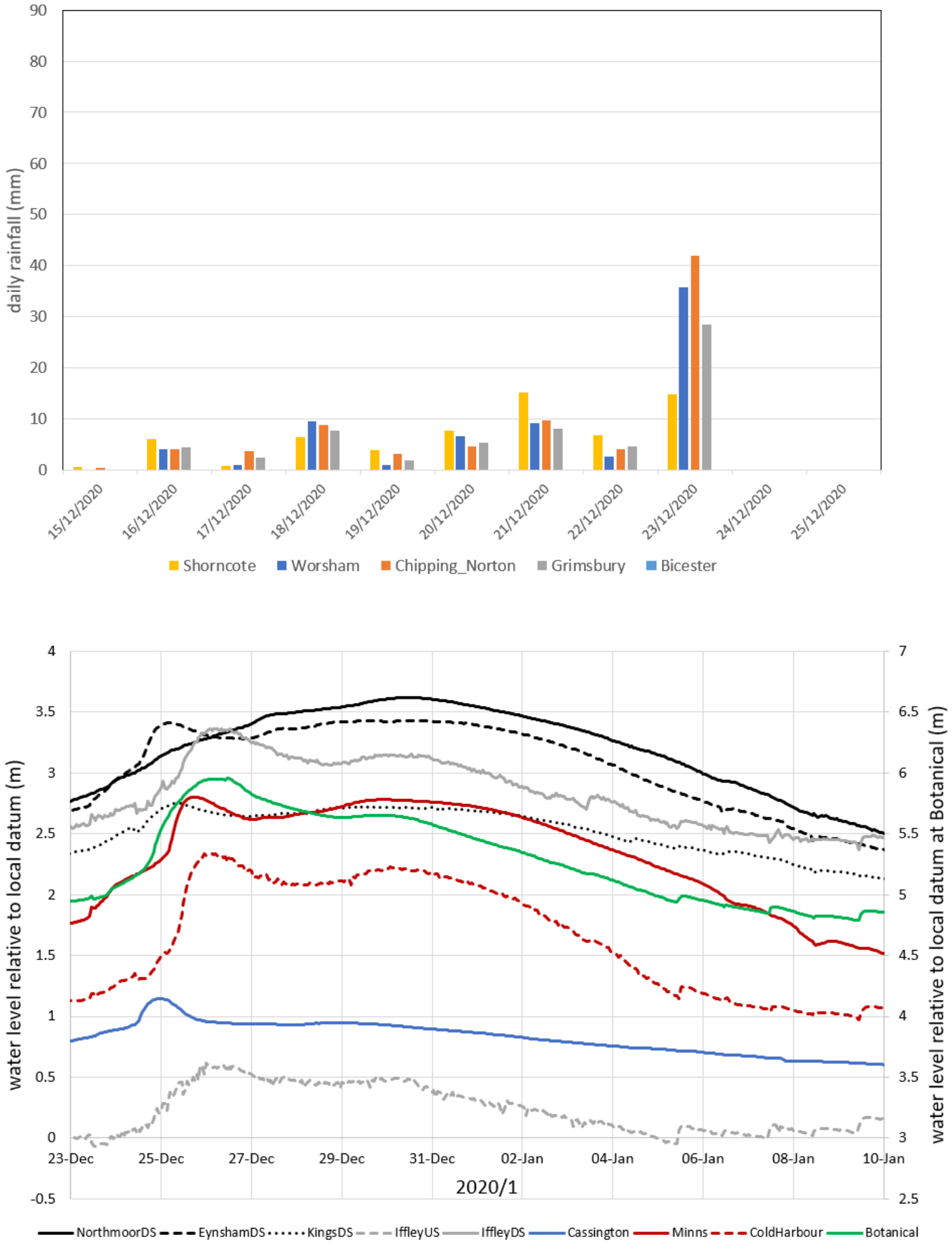


Figure 3-9 December 2020 flood: top - Rainfall at EA rain gauges within the Upper Thames, Evenlode and Cherwell catchments; bottom – hydrographs from river stations upstream of and within the Oxford floodplain

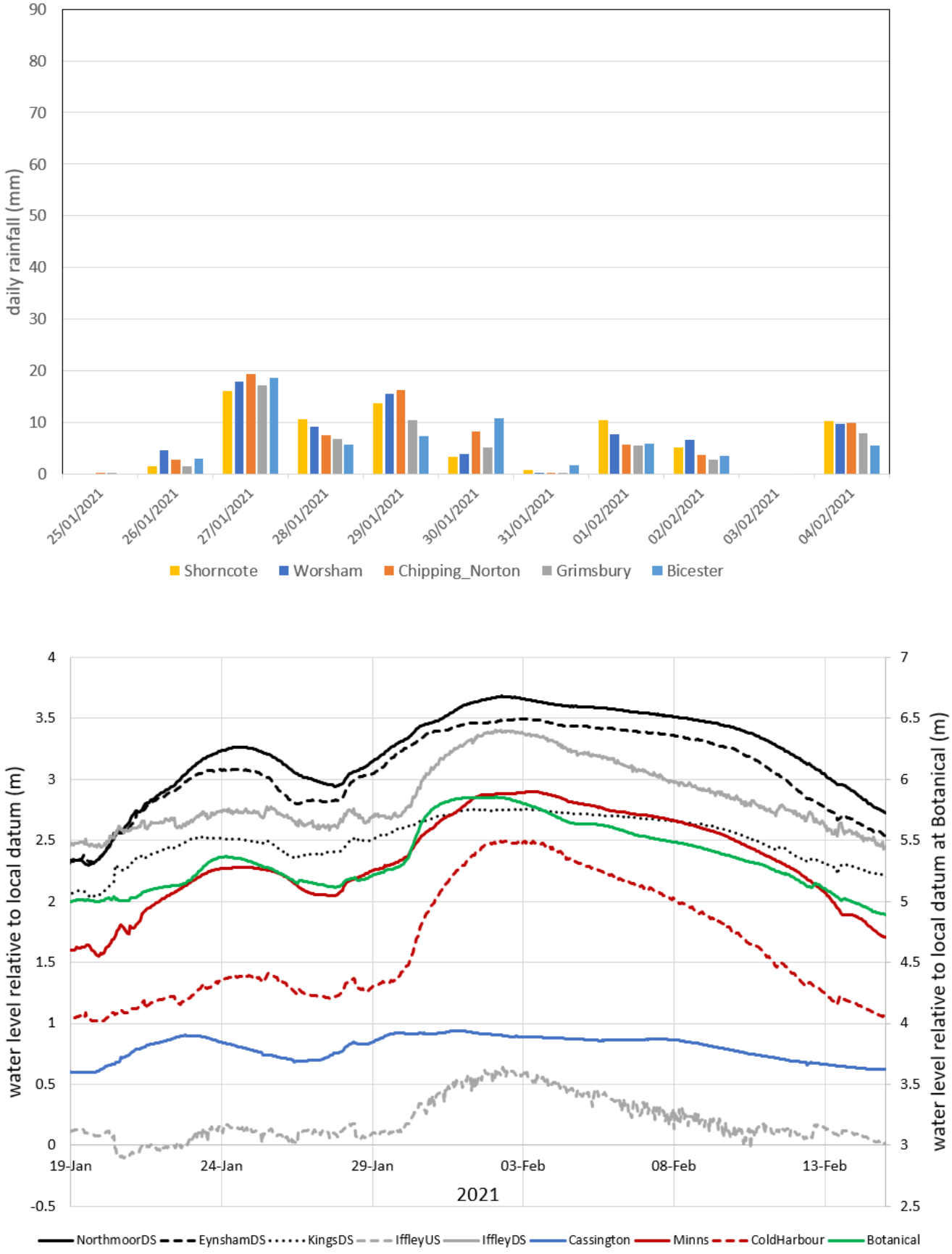


Figure 3-10 February 2021 flood: top - Rainfall at EA rain gauges within the Upper Thames, Evenlode and Cherwell catchments; bottom – hydrographs from river stations upstream of and within the Oxford floodplain

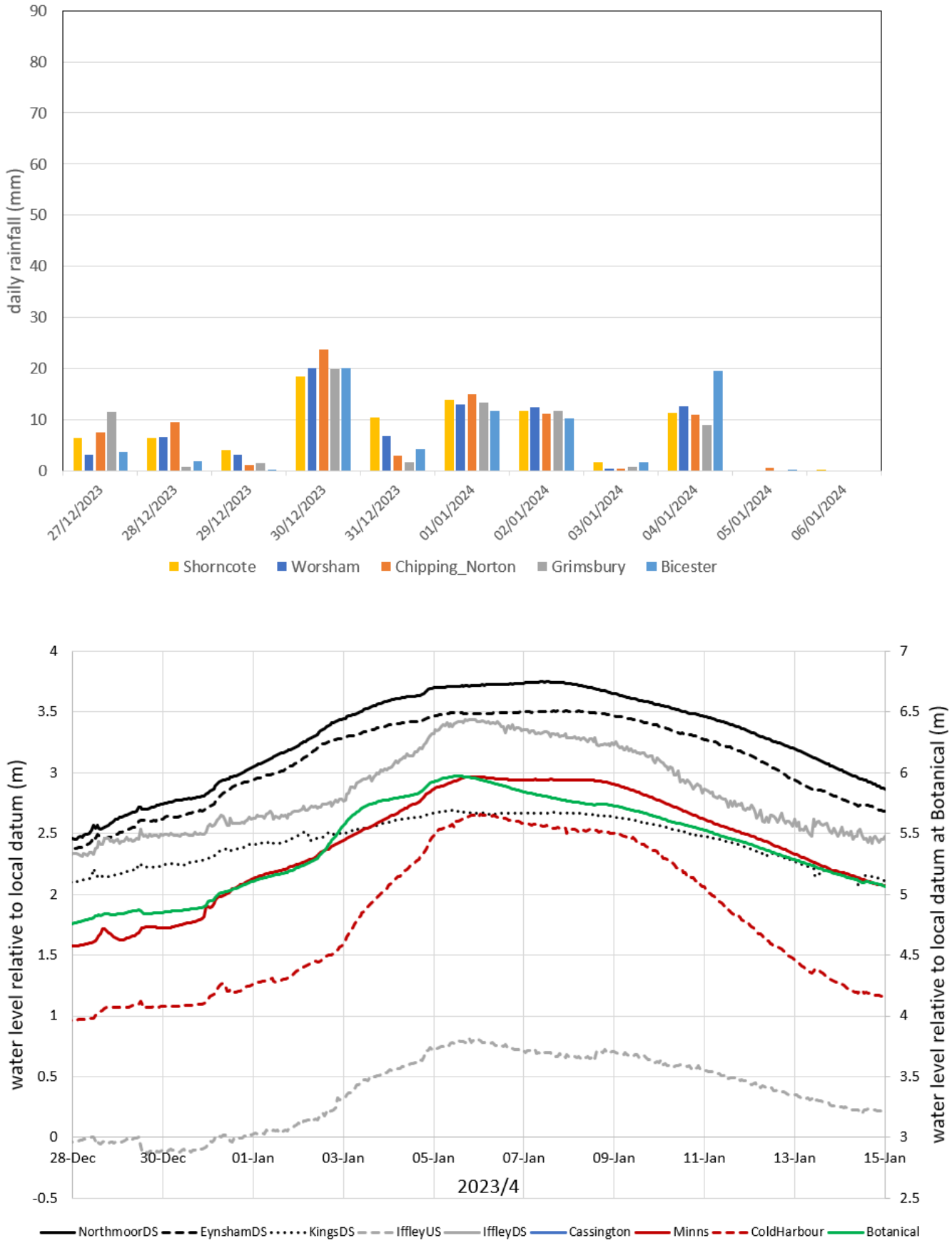


Figure 3-11 January 2024 flood: top - Rainfall at EA rain gauges within the Upper Thames, Evenlode and Cherwell catchments; bottom – hydrographs from river stations upstream of and within the Oxford floodplain

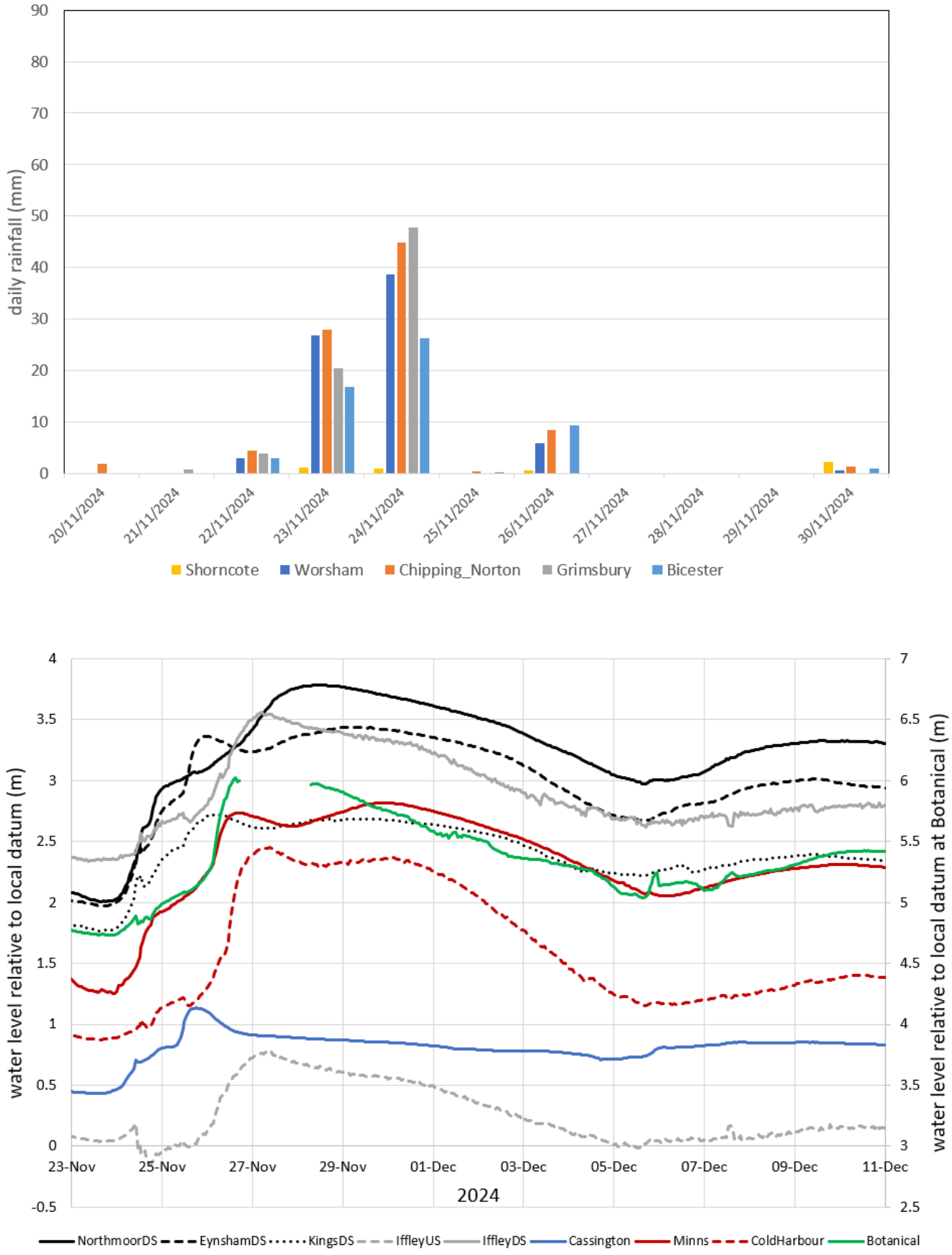


Figure 3-12 November 2024 flood: top - Rainfall at EA rain gauges within the Upper Thames, Evenlode and Cherwell catchments; bottom – hydrographs from river stations upstream of and within the Oxford floodplain

The analysis of these events helps to highlight a number of characteristics of flooding that will be relevant to early warning:

- Flooding in the Oxford floodplain can be generated by a wide range of rainfall patterns: very large events over one or two days (>60mm); a few events of smaller magnitude (~25mm) over a limited period; or a series of small events (~10mm) over several days, especially when antecedent river levels are above normal. On a number of occasions this latter situation has resulted in repeated flooding over a single winter. The more intensive the rainfall generating a flood the shorter and more rapid will be the onset of the flood.
- The distribution of rainfall within the catchments of the rivers feeding into the Oxford floodplain has a strong influence on the shape of the flood hydrograph.
- The height and timing of peak river levels during flood in the Seacourt and Hinksey Streams are dependent on both the Rivers Evenlode and Thames, although the Thames more often is the dominant control. The influence of the two rivers can cause two distinguishable peaks in the stream levels. As a result of the influence of the Evenlode, the initial peaks in Seacourt/Hinksey Streams can occur before the peaks in the Thames upstream of Oxford.
- The river level at Iffley Lock is dependent on the River Thames but also the River Cherwell, with the latter have a strong influence on the timing of the peak flows.
- As shown in Figures 2.10 and 2.11, groundwater levels within the urban areas of HPW follow a similar pattern to those of the Hinksey Stream and the River Thames.

3.4 TOWARDS EARLY WARNING

In this section we examine whether upstream river level thresholds can be identified that result in flooding in HPW and what lead-in times these provide. Note, the analyses in the following sub sections use hourly river level data.

3.4.1 Flood thresholds at HPW

River levels in the Hinksey Stream, River Thames and Weirs Mill Stream directly control fluvial flood water levels that affect HPW. Analysis in Section 3.2 has shown that there is also a strong correlation between river levels in the Hinksey Stream to the west of HPW and groundwater levels beneath the urban area of New Hinksey. Here we examine if river levels upstream of HPW can be correlated with the river levels in the vicinity of HPW that result in fluvial and groundwater flooding of property, that can potentially be used for early warning.

Firstly, we have assessed levels at the local EA river stations that are associated with property flooding. As discussed in Section 2.3, consultation was undertaken by Project Groundwater with members of the HPW to identify flood events that have occurred within recent decades that have resulted in major floods. A major flood is defined as one which results in: a significant number of properties, including gardens, being inundated; the sewerage system being compromised; and flooding on the Abingdon Road, at the junction with Weirs Lane, being sufficient to close or restrict passage through by vehicles. The consultation identified flood events from the late 1990s onwards.

The two EA river stations are on the boundaries of HPW are: Iffley Lock on the River Thames; and Cold Harbour on the Hinksey Stream. Analysis of the data confirmed that the highest river peaks coincided with the 13 periods during which residents reported major flooding had occurred in HPW. This gives confidence in the observations of the local residents and in the use of the river level data from the EA stations as a proxy for the occurrence of flooding. The maximum river levels downstream at Iffley Lock and in the Hinksey Stream at Cold Harbour that did not result in major flood events were 3.02 and 2.16 metres above the local datums

(mALD), respectively. The minimum peak water levels that did result in major floods were 3.33 mALD and 2.32 mALD, at Iffley Lock and Cold Harbour respectively. So, if flood thresholds are to be set based on the river station levels at these locations, they would be somewhere between these two levels.

Note, the Government Check for Flooding web site[1] includes the thresholds above which flooding of property is possible, as identified by the EA; further enquiries needed to find out how these have been estimated. The property flood threshold for the local area measured downstream at Iffley Lock Tail is 3.25 mALD and for Cold Harbour river station is 2.44 mALD.

3.4.2 EA Flood Warning for South Oxford area

The EA Flood Warning Service formally went live in January 2006. Data on the Flood Alerts and Warnings issued by the Service for the Oxford area since that time are reviewed here to assess how Alerts and Warnings issued compare with the major flood periods identified by local residents. The names and areas of Alerts have changed over the period since 2006; the point at which these changed has not been established but they are known for each Flood Warning issued. The Alert Area in 2007 and 2008 was named 'River Thames from Eynsham Lock, Eynsham to Sandford Lock, Sandford-on-Thames', so covered the whole of the floodplain of the River Thames in the Oxford area. For floods from 2012, a smaller area was delineated and named: 'River Thames and tributaries at New Botley, New and North Hinksey and Grandpont in Oxford' for floods from 2012 to 2021; and 'River Thames and tributaries at New Botley, New Hinksey, North Hinksey, South Hinksey and Grandpont' for floods from 2024 onwards.

In the period from January 2006 up to the end of 2024 there were 83 Flood Alerts and 12 Flood Warnings or Flood Warning Updates issued that covered these areas. The 12 Flood Warnings coincided with the major flood events identified by local residents that occurred within the period that the Flood Warning Service was operational. As groundwater flooding only occurred during the major floods, the Service also provided warnings for this form of flooding as well. Apart from a small number of properties in Cold Harbour which suffered from compromised wastewater drainage, the impacts of groundwater flooding did not affect HPW during periods in which Flood Alerts were issued that were not subsequently upgraded to Flood Warnings.

The times that the Flood Warnings and Flood Warning Updates were issued (and for information, the Flood Alerts that preceded these) are listed in Table 3.3. It is assumed, on the two occasions when the initial Warnings were followed by Warning Updates, that a recession following the initial peak in river levels was followed by another peak, a common characteristic of floods as described in Section 3.3.

In Table 3.3 the times of the Warnings and Updates are compared with the times that the river levels at the river stations at Iffley Lock (downstream) and Cold Harbour cross flood thresholds from the analysis in Section 3.4.1. In this current section, upper and lower boundaries of levels were identified for the two local river stations within which the onset of floods could occur. Single thresholds were chosen within these two ranges: for Iffley Lock (downstream) the threshold was set at 3.25m, the same as the flooding of property threshold defined by the EA; for Cold Harbour the threshold was set at 2.30m, the level at which the EA identified the flooding of low-lying land is possible.

At the two river stations there are wide ranges of differences in Warning times and the times at which the river levels pass these newly defined thresholds linked to flooding: for the Warnings, in all but two cases for Iffley Lock and one case for Cold Harbour, these occur before the flood thresholds are passed; Warnings have been as little as 1-2 hours; for both stations the warnings are more often less than one day. (Note, for floods for which Warning Updates were issued, the time closest to the time of the passing of the threshold was used.)

[1] https://check-for-flooding.service.gov.uk/

Table 3-3 Timings of Flood Warnings and Warning Updates (along with associated Flood Alerts) issued for HPW since 2006, and their relationship to the time that flood thresholds were passed at Iffley Lock (downstream) on the River Thames and Cold Harbour on the Hinksey Stream

Alert time	Warning time (Warning update)	Iffley Lock (downstream)		Cold Harbour	
		Passed 3.25m	Time after Warning	Passed 2.30m	Time after warning
20/07/2007 19:31	21/07/2007 21:16	23/07/2007 01:00	1d 3h	23/07/2007 02:00	1d 4h
12/01/2008 09:02	16/01/2008 14:35	ND		18/01/2008 03:00	1d 12h
22/11/2012 09:17	26/11/2012 08:43	26/11/2012 08:00	-1h	26/11/2012 18:00	9h
20/12/2012 10:34	24/12/2012 14:37	25/12/2012 03:00	12h	25/12/2012 13:00	22h
23/12/2013 19:27	04/01/2014 19:03	05/01/2014 09:00	13h	06/01/2014 04:00	1d 8h
	01/02/2014 14:07 09/02/2014 13:28	08/02/2014 05:00	6d 14h 1d 8h	08/02/2014 19:00	7d 4h 18h
21/12/2020 18:21	25/12/2020 16:20	25/12/2020 18:00	1h	25/12/2020 19:00	2h
21/01/2021 10:11	31/01/2021 18:03	31/01/2021 17:00	-1h	31/01/2021 19:00	-1h
31/12/2023 08:11	04/01/2024 09:30	04/01/2024 21:00	11h	04/01/2024 13:00	3h
24/11/2024 20:25	25/11/2024 19:51 29/11/2024 10:46	26/11/2024 14:00	18h -2d 20h	26/11/2024 18:00	22h -2d 16h

3.4.3 Developing flood warnings

An aim of this study was to explore the potential for early warning of flooding for HPW using upstream river levels. Are there upstream stations that have river level thresholds that are passed only during periods when flooding occurs in the HPW area that could be used to warn of impending flooding? A number of river stations in key locations were examined; these were located on the River Thames and on the main tributaries. The objective was to identify those stations furthest upstream that are reflective of subsequent flooding in HPW so as to maximise the period between warning and onset of serious flooding. This was undertaken at each river station by first identifying the minimum of the peak river levels associated with the 13 flood events in HPW, and then counting the number of times that threshold was crossed without flooding occurring in HPW. Where this number is high the station is not considered suitable as an indicator of future flooding in HPW.

Table 3.4 lists the stations assessed, along with: a description of the river that they are located on and their position on the river (the approximate distance upstream of HPW, from a location on a river in the HPW area with the Northing of 204700m); the threshold at that upstream station above which the 13 events in HPW flood events occurred; and the number of times that threshold was crossed but no flooding occurred at HPW.

Not unexpectedly, the peak river levels at the Minns Estate on the Seacourt Stream and at the Oxford Botanical on the River Cherwell reflected well the occurrence of floods in HPW, both stations being only a short distance upstream from HPW. Kings Mill, the nearest river station upstream of Oxford Botanical on the River Cherwell was not assessed as it is less than a kilometre away. The next upstream on the River Cherwell is Islip (although this is on the River Ray, it is on the confluence with the Cherwell). At this station the minimum river level that saw subsequent major flooding in HPW was crossed eight additional times. This is considered too high a number to provide sufficient certainty of the occurrence of flooding in HPW. No further stations on the River Cherwell were assessed.

Table 3-4 EA river stations upstream of HPW, the minimum peak water level that coincided with the 13 major flood events in HPW since 1998 and the number of times that level was crossed without flooding occurring in HPW. The river the stations are located on, the distance from the HPW (i.e. a location on the river at HPW with the Northing of 204700m), and a description of the river station

EA river station	River	Station description	Distance from HPW (km)	Min. peak level for 13 events in HPW (mALD)	Times min. peak level crossed since April 1998 without flooding at HPW
Minns Estate	Seacourt Stream	First station on the Hinksey Stream upstream of HPW	2.9	2.81	0
Oxford Botanical	River Cherwell	First station on the Cherwell upstream of the confluence with the River Thames	1.6	5.86	1
Islip	River Cherwell/Ray	Next station substantially upstream of the Oxford Botanical - at the confluence of the River Cherwell and the River Ray	11.8	8.79	8
Cassington Weir B	River Evenlode	First station on the Evenlode upstream of the confluence with the River Thames	10.3	0.94	12
Kings Lock (downstream)	River Thames	Downstream of the locations where the River Evenlode joins the Thames and the fixed weir from the Thames into the Seacourt Stream	8.1	2.65	3
Northmoor Lock (downstream)	River Thames	Next downstream after the confluence of the River Windrush with the River Thames	19.4	3.62	2
Shifford Lock (downstream)	River Thames	Last downstream before the confluence of the River Windrush with the River Thames	27.1	3.96	3
Rushey Lock (downstream)	River Thames	Next upstream from Shifford Lock	33.7	3.65	15

A similar situation occurred on the River Evenlode. The minimum river level that saw subsequent major flooding in HPW was crossed 12 additional times at the river station at Cassington Weir B. This station was therefore not considered a good one for predicting flood conditions in HPW. No stations further upstream on the River Evenlode were assessed.

On the River Thames the station nearest upstream from HPW assessed was Kings Lock (downstream). The minimum river level here that saw subsequent major flooding in HPW is a relatively good predictor, as this was only exceeded three additional times. Moving upstream, the next stations assessed were Northmoor Lock and Shifford Lock (both using level on the downstream side of each lock). Here the minimum river level thresholds for major flooding in HPW were only exceeded an additional two and three times, respectively. This was perhaps surprising given that the River Windrush joins the Thames between these two stations (there is no long-term river level data for the Newington river station on the Windrush upstream of the confluence with the River Thames). However, at the next station upstream on the River Thames, Rushey Lock, the minimum river level threshold for major flooding in HPW was exceeded an additional 15 times, indicating this station is not a good predictor.

Having identified stations that have river level thresholds that appear good predictors of flood conditions in HPW, estimates of the lags in river level responses between these stations and the river levels at HPW were

made. Predictor time series used were those in Table 3.4 with thresholds crossed fewer than or equal to three times. These were paired with the two target EA river stations in the HPW area, Cold Harbour and Iffley Lock (downstream). The target station chosen for each predictor was based on hydrological connections; the Thames at both Shifford and Northmoor Locks is linked to the Hinksey Stream and the River Thames at Iffley Lock. The lag between the two time series for each pair was calculated separately for the highest 5% and the highest 1% of the HPW river station levels; the Pearson's Correlation Coefficients between the two time series were also calculated.

Table 3-5 Lags and Pearson's Correlation Coefficients for pairs of river stations at HPW and upstream, using the highest 5% and 1% of HPW station river level data

Predictor river station	HPW river station	Highest 5%		Highest 1%	
		Lag (h)	Correl. Coeff.	Lag (h)	Correl. Coeff.
Shifford Lock (downstream)	Hinksey Stream at Cold Harbour	+11	0.74	+13	0.58
Northmoor Lock (downstream)		+3	0.81	-1	0.58
Minns Estate		+2	0.92	+3	0.89
Shifford Lock (downstream)	Iffley Lock (downstream)	+7	0.58	-1	0.44
Northmoor Lock (downstream)		-2	0.74	-11	0.60
Kings Lock (downstream)		+10	0.67	+16	0.38
Oxford Botanical		+3	0.87	+6	0.78

A few significant inconsistencies were identified through the analysis:

- the lags in the time series did not reduce with distance from the predictor to the target time series in all cases;
- the lags did not change consistently from the highest 5% to 1% across the pairings;
- the difference in the lags between Shifford Lock and Cold Harbour, and Shifford and Iffley were greater than expected. This was also the case for Northmoor Lock.

It may be that further analysis of the data identifies the route of these inconsistencies. This could be caused by the different influences on the flood levels in the HPW area due to rainfall distribution/river response. An event-based approach to lag definition might be more appropriate.

4 WAY FORWARD

4.1 HINKSEY PARK WARD

The analysis undertaken here has shown the complexity of flooding that occurs in HPW, as a result of the number of rivers and streams that border it and their differing catchment responses to rainfall. Section 3.2 provided evidence to confirm the expected strong correlation between local river levels and groundwater levels beneath HPW. Given the complexity of flood responses, in the time it has been running, the EA Flood Warning Service has still managed to identify all major (as defined here) flood events. However, based on the local flood thresholds estimated through this study, the lead-in times provided by the Service are variable and have been on occasions quite short; knowledge of the methodology used by the EA to develop their alerts and warnings would help in understanding why this is the case.

It has been possible to identify threshold river levels at upstream river stations that identify periods of major floods that occur in HPW. As expected, the number of false positives increases with distance upstream. Those

stations with three or fewer false positives were identified in Section 3.4.3 but the lags between the levels at these river stations and at those local to HPW during high flow periods were inconsistent. This is likely due to the range of flood characteristics highlighted in Section 3.3. The one relationship that could potentially be used is that between Shifford Lock on the River Thames and Cold Harbour on the Hinksey Stream although at ~12 hours for river levels the lag might still be considered relatively short as a warning.

In the settings where PSD groundwater flooding occurs, it is rarely possible to separate the drivers, the mechanisms and the impacts from those of fluvial flooding. Warnings therefore need to encompass both forms of flooding. The analysis in Section 3.2 shows a range of lag times between river levels and groundwater levels. In the case of borehole NH1, located in a central area of New Hinksey, the lag between the Hinksey Stream and the groundwater level is ~20 hours, significantly more than the lag between Shifford Lock and Cold Harbour river levels. Together, the lag between Shifford Lock river level and groundwater levels in the borehole in New Hinksey is of the order of 1.5 days.

However, the uncertainties in forecasting the onset of serious flood impacts are notable: in the river level response locally during floods; and in the spatial variation in groundwater levels, both due to proximity of locations to the rivers as well as the elevation of receptors. What the analysis in Sections 3.4.2 and 3.4.3 has provided are levels at EA river stations upstream of and local to HPW that correlate with the onset of major flooding in the area. This is useful information for the residents of HPW, as the flood thresholds given on the Government 'Check for Flooding' web pages for upstream river stations do not relate to HPW, and the validity of these thresholds in stations local to HPW are questionable. Although not considered here, extrapolation of rising hydrographs at upstream river stations could be undertaken during floods and provide days rather than hours of warning of major flooding. Conversely, the same approach may also provide reassurance that a developing flood is unlikely to be significant; feedback from many residents within HPW highlights the anxieties experienced, particularly amongst vulnerable groups, even during routine smaller floods that occur on a regular basis. Of the EA Flood Alerts that were issued that applied to the HPW area, 86% did not lead to Flood Warnings, and the impacts of the floods were limited.

In the HPW area, PG has helped with the establishment of the South Oxford Flood Action Group (SOFLAG), run by local residents. Through an Innovation Grant provided by PG to SOFLAG, the group has developed a web site that ingests live river level data through the EA API and presents these along with its own live groundwater and stream level data. Guidance is provided for interpretation of the data by residents. This includes some of the threshold level information discussed in this report and, with appropriate acknowledgement of the uncertainty, specific reference to the lag between Shifford Lock and Hinksey Stream levels. This aspect of the web site was launched in January 2026 and it will take time to raise its profile. In the mean time during the February 2026 flood event a member of SOFLAG provided a daily summary of flood conditions using the live data streams and local knowledge, disseminated through a community WhatsApp group, with very positive feedback.

The monitoring network developed by SOFLAG through the Innovation Grant will gather further data in the coming years that, along with further analysis of existing river and groundwater level time series, is expected to provide greater insight into the hydrological response during periods of flooding, including local thresholds. It is hoped that this will also provide greater warning of impending serious flooding.

4.2 WIDER APPLICATION

Results from the analysis here, and experience from its application in the HPW context, indicates that live river level data available through the EA network can be useful in the context of early warning for PSD groundwater flood-prone communities. Here we have confirmed, as previously known, river level information can be used to infer groundwater conditions in PSDs. However, superficial deposits are often

spatially heterogeneous in lithology and aquifer properties, and river bed properties can limit the hydraulic connection. Therefore, it is preferable to have some local evidence of groundwater response to rivers, whether that is through monitoring infrastructure or observations of groundwater flooding.

Although HPW has been shown to be a complex flood setting, circumstances in other locations may be simpler and warning times of floods (with a groundwater component) that are longer and of lower uncertainty may be possible. It is unlikely, however, that early warning systems can be implemented without some local knowledge that brings detailed understanding of receptors and information on past flood events. The value of local flood groups is clear; these can provide ongoing support, helping to interpret data for other residents and improving systems for future floods based on the new data collected. Local groups may also be able to tap into funding streams that allow monitoring infrastructure to be installed that allow information to be collected that complements the EA river monitoring network. For example, the cost of drilling shallow boreholes for groundwater level monitoring may not be prohibitive.

5 REFERENCES

Black & Veatch, 2009. Oxford Flood Risk Management Strategy Hydrogeological Review. Black & Veatch Report.

Dixon, A. J., 2004. The hydrology of Oxford Meadows cSAC. Environment Agency Report.

Dixon, A.J., Bradford, R.B, Cooper, D.M., Reeve, C.R. & Tucker, D.K. (1990) A hydrological assessment of the impact of proposed sand and gravel extraction on an adjacent ecologically sensitive floodplain environment - a case study. In: Gaskarth, J.W. and Lumsden A.C. (eds). Proc. of 6th Extractive Industry Geol. Conf. Birmingham University, 70-81.

Environment Agency, 2003. Oxford Strategy Study: Questionnaire Survey Report on past flooding in Oxford. Environment Agency Report.

Environment Agency, 2009. Oxford Flood Risk Management Strategy Hydraulic Modelling - Model Build & Calibration Final Report. Environment Agency Report

Gardner, C.M.K., 1991. Water regime of river meadows: Yarnton Mead case study. Institute of Hydrology Report to River and Coastal Engineering Group, Ministry of Agriculture Fisheries and Food.

Gooddy, D. C., Macdonald, D. M. J., Lapworth, D. J., Bennett, S. A., & Griffiths, K. J. (2014). Nitrogen sources, transport and processing in peri-urban floodplains. Science of the total environment, 494, 28-38.

Gowing, D. & Youngs, E., 2005. The requirements of Apium repens – an ecohydrological assessment, Final Report. Institute of Water and Environment, Cranfield University.

Hodgson, R., 2008. Groundwater and flooding in Oxford: examining key soil processes. University of Reading MSc dissertation.

Macdonald, D. M. J., Dixon, A. J., & Gooddy, D. C. (2018). Water and nitrate exchange between a managed river and peri-urban floodplain aquifer: Quantification and management implications. Ecological Engineering, 123, 226-237.

Macdonald, D. M. J., Dixon, A., Newell, A., & Hallaways, A. (2012). Groundwater flooding within an urbanised flood plain. Journal of Flood Risk Management, 5(1), 68-80.

Newell, 2008. Morphology and Quaternary geology of the Thames floodplain around Oxford. British Geological Survey Technical Report.

Schofield, D., Lewis, M., Smedley, P., Bloomfield, J. & Boon D., 2014. Illustrative Components of the Geological Environment. British Geological Survey Internal Report, CR/14/132.